CODEN STJSAO ISSN 0562-1887
ZX470/1397 UDK 621.316.1:621.317.78.088

Measurement Procedure for Commercial Loss Reduction in a Distribution Power System

***Marinko STOJKOV*[1]*, Drago ŽAGAR*[2] and *Kruno TRUPINIĆ*[3]**

1) Strojarski fakultet u Slavonskom Brodu Sveučilišta J. J. Strossmayera u Osijeku (Mechanical Engineering Faculty, J. J. Strossmayer University of Osijek), Trg Ivane Brlić-Mažuranić 2, HR-35000 Slavonski Brod, **Republic of Croatia**

2) Elektrotehnički fakultet Osijek Sveučilišta J. J. Strossmayera u Osijeku (Faculty of Electrical Engineering, J. J. Strossmayer University of Osijek), Kneza Trpimira 2B, HR-31000 Osijek, **Republic of Croatia**

3) HEP-ODS, Elektra Slavonski Brod, Petra Krešimira IV. 11, HR-35000 Slavonski Brod, **Republic of Croatia**

marinko.stojkov@hep.hr

Keywords

Commercial Power Losses
Distribution Power System
Illegal Connection
Response in form of voltage pulse

Ključne riječi

Distribucijski elektroenergetski sustav
Nelegalan priključak
Netehnički gubici energije
Odziv u obliku naponskog vala

Received (primljeno): 2009-01-25
Accepted (prihvaćeno): 2009-06-20

Subject review

Total power losses in a power system consist of technical losses and commercial losses. Commercial losses are 30-40 % of total losses and appear as a result of unreliable measurement devices for electricity registering and wilful unauthorised consumption of electricity. It is almost impossible to find illegal connections in a distribution power system due to hidden main power cables in the house walls or underground. A proposed and elaborated measurement procedure based on time domain reflectometer successfully solves the problem described.

Mjerna procedura za smanjivanje netehničkih gubitaka u distribucijskom elektroenergetskom sustavu

Pregledni članak

Ukupni gubitci energije u elektroenergetskom sustavu sastoje se od tehničkih i netehničkih gubitaka. Komercijalni ili netehnički gubici čine 30-40 % ukupnih gubitaka i nastaju kao posljedica nepouzdanih mjernih uređaja za registriranje utroška električne energije i uslijed namjerne nepovlasne potrošnje. Gotovo je nemoguće pronaći ilegalno izveden priključni kabel u distributivnom elektroenergetskom sustavu jer se glavni priključni kabeli nalaze u zidovima kuće ili ispod zemlje. Predložena i razrađena mjerna procedura koja se bazira na primjeni reflektometra u vremenskoj domeni uspješno rješava opisani problem.

1. Introduction

Total losses of energy in a distribution power system consist of technical and commercial power losses. Although total power losses are a physical category which is easy to understand, it is not so easy to evaluate. They are determined as a difference between income (input) energy from transmission system and/or power plants during a time period and the sum of supplied (output) energies to all consumers in a distribution power system during the same time period.

Causes of technical losses of energy are heating of transformers, cables and wires, transformer core magnetizing all the time even without a load, forced cooling of transformers during extreme load conditions and isolation imperfections. Evaluation of technical losses of energy in a distribution network is very complex because of a great number of transformer substations, power lines of different lengths, and end-users connected to different voltage levels and even without symmetry in a distribution power system. The amount of technical losses depends on the network's size, power line's nature, distribution and distance of consumers etc. However, it is possible to make a decision during realization of maintenance or planning policy to improve efficiency and reduce losses [1].

Commercial losses of energy are unpaid consumption and they are calculated as a difference between total losses

Symbols/Oznake

LV	- Low Voltage - niski napon
PVF	- Propagation Velocity Factor - faktor brzine širenja
TDR	- Time Domain Reflectometer - reflektometar u vremenskoj domeni
L_1, L_2, L_3	- IEC marks for conductors/busbars of different phases - IEC oznake za vodiče/sabirnice različitih faza
N	- IEC mark for neutral conductor/busbar - IEC oznaka za neutralni vodič/sabirnicu

and technical losses of energy. In contrast with technical losses, it is very hard to establish a general procedure to decrease commercial losses because it is not so easy to locate exact sites where they arise [2].

Possible causes of commercial losses of energy are end-users with under measured registered electric energy (usually too old electricity meters or faulty connected indirect electricity meters) and the existence of illegal taps, intentionally made and completely without registering energy (stealing).

The amount of commercial losses of energy on low voltage (LV) network is mainly due to the percentage of end-users on LV network according to all consumers. Electricity stealing from supplier depends on consumer's payability, his integrity and legislation penalties. It could cause deep effects in the power quality (voltage range and voltage flickers) for electric devices and installations of other end-users. LV distribution network is either overhead or underground, built mostly on public areas. In any circumstances, it is not so easy to make an illegal tap directly on the network under voltage. The overhead network is visible all the time, which makes it impossible to carry out the illegal tap. If someone even makes an illegal connection, it is not hidden and aftera short time the illegal consumer has serious problems. In contrast, underground lines are completely hidden and skilled cable technique activities have to be done on the power cable to make an illegal tap. So, theft of electric energy does not take place on the network itself, but on the consumer's connections. Usually, the main consumer's cable feeding point is an underground or overhead network, it passes hidden through house walls, lofts or underground at least several meters before it is connected to the electricity counter (inside house) and after to the consumer's electric installation. Consequently, illegal taps are located between the house service entrance and the metering point, inside the bulding walls, under the roof or in the basement [3].

Here in a measurement procedure it is proposed to inspect the main power connection, to detect eventually existing illegally taps and determine the exact location of theft of electrical energy based on Time Domain Reflectometer (TDR), all with the purpose to reduce commercial losses in distribution network. A brand new idea is to use a different response to recognize illegal tap connection(s) on the main power cable – here the point of discontinuity is line-two (or even more) existing lines. It is usually very hard to find out the end-user′s main cable with illegal connection, especially to prove it by detection of a stolen cable. Now, it is easy to check any type of the main consumer's power cables. The described procedure herein reduces commercial losses and simultaneously improves quality and commercial efficiency of a power system.

2. Mathematical model based on an electric line theory

2.1. Basic principles

Although an electric line is continuously distributed in its nature, it is usually modeled by partial concentrated electric parameters pitched along the electric line's length. The model consists of values of four parameters (per unit length), depending on type of cable and manner of mounting: conductor's resistance R_1, conductor's inductance L_1 , conductance of the dielectric G_1 and capacitance between the conductors C_1. Values of unit resistance and unit conductance are zero for an ideal power line without losses, which is useful neglecting for short cables.

There are three types of traveling waves in a transmission an electric line theory: initial, forward and reflected traveling waves. The energy of electric field transforms into energy of a magnetic field and inverse on discontinuity points on a power cable. Such points exist wherever it comes to change of wave impedance Z_0, such as a line-bus, line-line, line-load point or line-more lines passage point. According to energy conservation law, the sum of electric and magnetic energy of initial wave is constant - of course, it is like that only for an ideal power line. When an initial traveling wave attains a discontinuity spot on a power cable, the described point becomes a now source of two new waves: forward (transmitted) and reflected wave. Here, magnitudes and velocities of waves are usually not of the same size as the initial wave.

2.2. Characteristic wave impedance of electric line Z_0

This parameter of electric line (underground or overhead) is the ratio between momentary values of the voltage and the current for an infinitely long line. It depends on the geometric parameter of the conductor and isolation, type of isolation and distances between conductors of the same and different phases, but it does not depend on line length. Equation (1) describes a mathematical expression of characteristic wave impedance for general electric line and equation (2) gives the same impedance for ideal electric line (R_1=0, G_1=0).

$$Z_0 = \sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}}, \Omega \,, \tag{1}$$

$$Z_0 = \sqrt{\frac{L_1}{C_1}}, \Omega \,. \tag{2}$$

2.3. Propagation Velocity Factor (PVF)

According to the electric line theory, the momentary values of an electric voltage (or current) are the function of two independent variables: time (t) and distance (x). Propagation velocity factor denotes how isolation type and geometry of the main power connection cable affects the speed of traveling waves along the cable. It is very important in acquiring the accuracy of time-length distance between cable end and discontinuity points of the cable. The voltage magnitude after traveling down the cable is attenuated comparing the voltage magnitude of an initial wave by factor α (nepers per unit length) as well as voltage phase which is shifted by factor β (radians per unit length); so propagation constant γ is defined as (3):

$$\gamma = \alpha + j\beta = \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)}. \tag{3}$$

For an ideal electric line without losses, PVF is defined as (4):

$$PVF = \frac{1}{\sqrt{L_1 \cdot C_1}} = \frac{1}{\sqrt{\mu \cdot \varepsilon}} \,. \tag{4}$$

Relative permittivity and permeability of the cable are basic parameters for calculating PVF. It is usually expressed in a relative attitude against vacuum light velocity c (1 or 100 %). PVF in coaxial cable is 0,85, in a twisted pair telephone cable it is 0,65 and in a power cable it is 0,5. Real value of PVF for chosen cable type is given as a ratio of measured length of cable and half time measured from generaton of an initial wave (end of cable) to time accepting reflection wave at the same end of the cable. Relative permittivity for overhead lines is 1, so PVF is c. The same parameter for some types of cable is 4 which gives PVF value $c/2$ [4].

Here, an expression (5) is used:

$$PVF = \frac{c}{\sqrt{\varepsilon_r}} \,. \tag{5}$$

2.4. Voltage reflection coefficient

The magnitude of a reflected voltage wave varies from the magnitude of an initial traveling wave, depending on impedance (Z) at the discontinuity line point. Here, the assumption is a lossfree case: the reflected wave is of equal magnitude at the line starting point and during propagation back up the line towards the source of initial wave (negligible choke). Voltage reflection coefficient of cable type could be its quality mark, given as a ratio between the reflected wave magnitude and an initial wave magnitude:

$$r = \frac{U_R}{U_P} = \frac{Z - Z_0}{Z + Z_0} \cdot 100\,\% \,, \tag{6}$$

where Z = impedance at point with discontinuity along the cable (illegally connected cable) and Z_0 = characteristic cable impedance.

2.5. Characteristic response waves

There are several characteristic possible discontinuities of impedances and accompanying response waves.

A) Conductor expiration in isolation (Z=∞)

The voltage reflection coefficient is given by an equation (7):

$$r = \frac{\infty - Z_0}{\infty + Z_0} \cdot 100\,\% = +100\,\% \,. \tag{7}$$

Reflected wave of opened end or on conductor expiration in isolation (failure) is the same as the initial wave, of the same polarity with opposite direction. In real nature magnitude of reflected wave it is several percent weaker than the magnitude of the initial wave due to energy losses on the measured cable (Figure 1A).

B) Short connected conductors (Z=0)

The voltage reflection coefficient is calculated by an expression (8):

$$r = \frac{0 - Z_0}{0 + Z_0} \cdot 100\,\% = -100\,\% \,. \tag{8}$$

The reflected wave in that case is of the same magnitude but of opposite polarity and direction of wave spreading (Figure 1B).

C) Connection of two cables of the same type (Z=Z_0)
The voltage reflection coefficient is given by equation (9):

$$r = \frac{Z_0 - Z_0}{Z_0 + Z_0} \cdot 100\,\% = 0\,. \tag{9}$$

Strictly mathematically concluded, at the connection of two cables of the same type there is no kind of reflection. But in the real world, the reflected pulse of very low magnitude appears due to a change of impedance (change in geometry of conductors and isolation), Figure 1C. The remaining part of the initial pulse passes further in the second cable almost of the same magnitude as the initial pulse. The same situation is if the cable is closed with an electric device with the same impedance as the first cable.

D) and E) Connection of cables of different types

There is a partial reflection with polarity and magnitude in dependence on Z_0 and Z_1. If the impedance of the second cable is less than the impedance of the first cable (Z_1<Z_0), the voltage reflection coefficient is negative and less then 100 %, Figure 1D. If Z_1>Z_0 then the reflected wave appears, where r is positive and magnitude is again less than 100 %, Figure 1E.

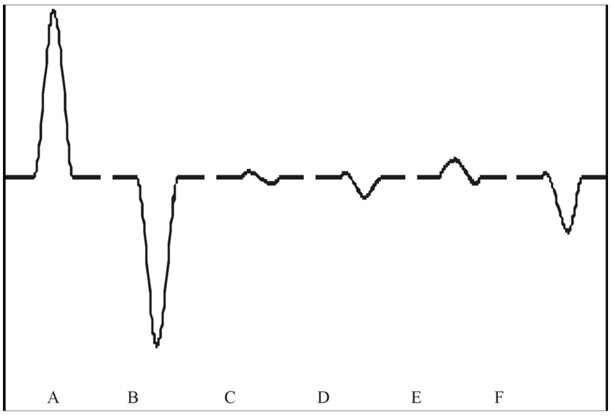

Figure 1. Characteristic reflected pulse shapes
Slika 1. Karakteristični odzivi reflektiranih valova

Following characteristic reflected pulse shapes on real cables registered by TDR are shown in 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

2.6. Reflected wave shapes

At the point with change of impedance the shape of the reflected waves varies in its magnitude and polarity. The characteristic shape of the reflected wave, after detailed analysis, gives information about the cable isolation state, possible unusual connections or cable fault state. Boundary cable states are open circuit (high impedance) and short circuit (low impedance shunt). Other cable states (between above mentioned two states) are based on different cable junction (series impedance of two cable types), cable fault (partial parallel impedance) and illegal tap on main power cable.

3. Time-Domain Reflectometer (TDR)

3.1. Function principles

A TDR is an electronic instrument used in different fields such as geotechnical (stability monitoring), level measurement (distance and temperature), agriculture (moisture content) and electric engineering. For example, TDR is applied in detecting failures of printed circuit boards and semiconductors, testing of integrated circuits and preventive maintenance practicing of telecommunication systems (cable monitoring, isolation failure diagnostics and measurement of cable lengths). TDR is connected between two conductors at one end (initial) of the cable. It sends a short rise time wave along the cable. At the discontinuity point two brand new waves arise (reflected toward TDR and transmitted toward far end of the cable) with different speeds depending on type of isolation on every side of the point with an impedance change. A distance between the initial end of the cable and discontinuity point is indirectly measured by the sum of time needed for the initial wave come to the characteristic point and time needed for the reflected wave to pass back to the initial end of the cable and known speed of the wave. The distance is calculated by multiplying the known speed of wave in the first cable part and total time of wave propagation. TDR advisable use in proposed procedure needs to have recommended features:

- minimal measure range as less as possible (less then 10 m),
- possibility to zoom pulses with better resolution to look for details along its natural very short main power cables,
- as shorter pulse duration as possible to easy distinguish pulses without covering (less then 10 ns),
- magnitudes of initial pulse modulated 0-10 V,
- output directed impedance close to main connection cable (25-100 Ω, here – for power cables 50 Ω)

to decrease dampening factor and better insight in starting share of cable,

- possibility to enhance reflected waves (gain for example 60 dB) to improve clearness,
- possibility to regulate PVF to get better measured distances for standard cable types (50-80 % of *c*),
- isolation proofed instrument possible to test connection cable under voltage conditions (1000 V),
- built-in filter to reduce disturbances,
- possibility to measure decrement of wave magnitude (return loss),
- at least two movable cursors to improve simple determination of lengths between any two points along the cable.

TDR is a device usually used for testing telecommunication cables and sometimes for power cables; wherever there are no direct connections with the ground. It consists of simplified oscilloscope and signal generator. A testing method is performed in phases, depending on a number of conductors inside the cable. Two tested conductors at the cable far end have to be connected together to exactly detect the length of the cable (characteristic junction or failure point). The incident, transmitted and reflected pulse are registered and stored by the oscilloscope at a cable definite point [5].

3.2. Illegal connection shape of pulse response

If an illegal connection on a mail power cable exists, the initial wave entries on impedance Z_{p00p} consist of characteristic impedance of illegal cable Z_{0p} and characteristic main power cable impedance Z_0 (tested), parallely connected at tap point (10):

$$Z_{p00p} = \frac{Z_{0p} Z_0}{Z_{0p} + Z_0}. \tag{10}$$

According to equations (6) and (10) voltage reflection coefficient follows in (11) and (12):

$$r = \frac{\dfrac{Z_{0p} Z_0}{Z_{0p} + Z_0} - Z_0}{\dfrac{Z_{0p} Z_0}{Z_{0p} + Z_0} + Z_0} = -\frac{Z_0}{2Z_{0p} + Z_0}, \tag{11}$$

$$r = \frac{-1}{1 + \dfrac{2 \cdot Z_{0P}}{Z_0}} \cdot 100\,\%. \tag{12}$$

Voltage reflection coefficient is negative which means that the reflected wave is of inverse polarity shape relating to initial wave, independent of an illegal cable (type, length or impedance) [6].

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

4. Proposed measurement procedure based on research

4.1. Measurement procedures defined by location

Here proposed measurement procedure aimed at commercial loss reduction is divided into two segments by part of the main power cable under testing (location and voltage conditions):

- the connected cable section between house main fuses and electric energy registration device (open cable on both ends – without voltage and continual electricity supply for a customer),
- the connected cable section under voltage between house main fuses and distribution low voltage network (overhead or underground).

4.2. Main power cable testing without voltage (overview of all cases)

The following steps of proposed measurement procedure during testing of saction of the connection cable between house main fuses and electric energy registration device are listed in steps:

a) Switch off the main fuses to get the cable without voltage so we have a “clean” cable to test, opened at both ends.

b) TDR is connected between two conductors (for example L_1-L_2) of the cable at one end; TDR parameters are set (measurement range, pulse width, gain, PVF). Reflected and transmitted waves are recorded by TDR.

c) Now the same conductors of previous step need to be short connected at the far end of tested cable. Again, reflected and transmitted waves are recorded by TDR. Comparing two recorded reflected pulses, better said changes between two pulses, characteristic points of the impedance change (at least cable end) are defined and exact length of the cable is determined.

d) Steps b) and c) have to be repeated six times to do the same for all electrical phases (L_1, L_2 and L_3) and neutral conductor (N) combinations so as to compare responses of different pairs of measured conductors at the same end of the cable.

e) If the tested connection cable is correct, which means without illegal t-connection, three expected recorded pulses are very clearly visible: transmitted pulse of TDR measurement device, crossing pulse at junction between measurement cables and close end of the tested cable and reflected pulse at the far end of the same cable. The last one varies in its shape and magnitude depending on open or short circuit of far cable end.

If there is a doubt about unexpected disturbance on a given pulse, the TDR device can be connected to the opposite end of tested cable to try for certain suspicious cable segments to be seen more clearly. In this way, some problems which are turned up by tiling of reflected pulse on illegal junction spot with crossing pulse on junction measurement cables - tested main power cable could be successfully avoided. The same problem is solved by using additional cable with length of 2-5 m between TDR measurement cable and tested cable to reduce disturbances due to transmitted pulse of TDR. It is especially prosperous during searching with greater width (energy) pulses.

In the case an illegal existing connection on the main power cable, the reflectometer registers additional response pulse on the tap point and response pulse from the far end of illegal cable (open) or eventual response pulse of connected part of the electric installation (cable end closed by impedance). It is recommended to use zoom and gain functions of TDR to notice and analyze response pulses. Furthermore, return loss function (magnitude decrease of reflected pulse on main cable end) and difference function of two response pulses (open end and short connected end cases) could be applied too to increase reliability of cable detection. Here, record of the reflected pulse is changed, depending on the distance from close end of the main power cable, type of illegal junction of two cables and type of illegal cable. So, here are the following influence circumstances and their combinations:

1. The junction point of illegal connection closer to the feeding cable end, exactly in the middle of the cable length or closer to customer end of main power cable

The junction point of illegal connection is better observed if the reflectometer is connected to closer end to tap spot because of pulse attenuation in real cable. Response wave of illegal junction is presented in figure 1F.

2. Shorter or longer cables of illegal connection

Longer length of the illegal cable results in better visibility of illegal cable reflected pulse as well as reflected pulse extra attenuation of main power cable

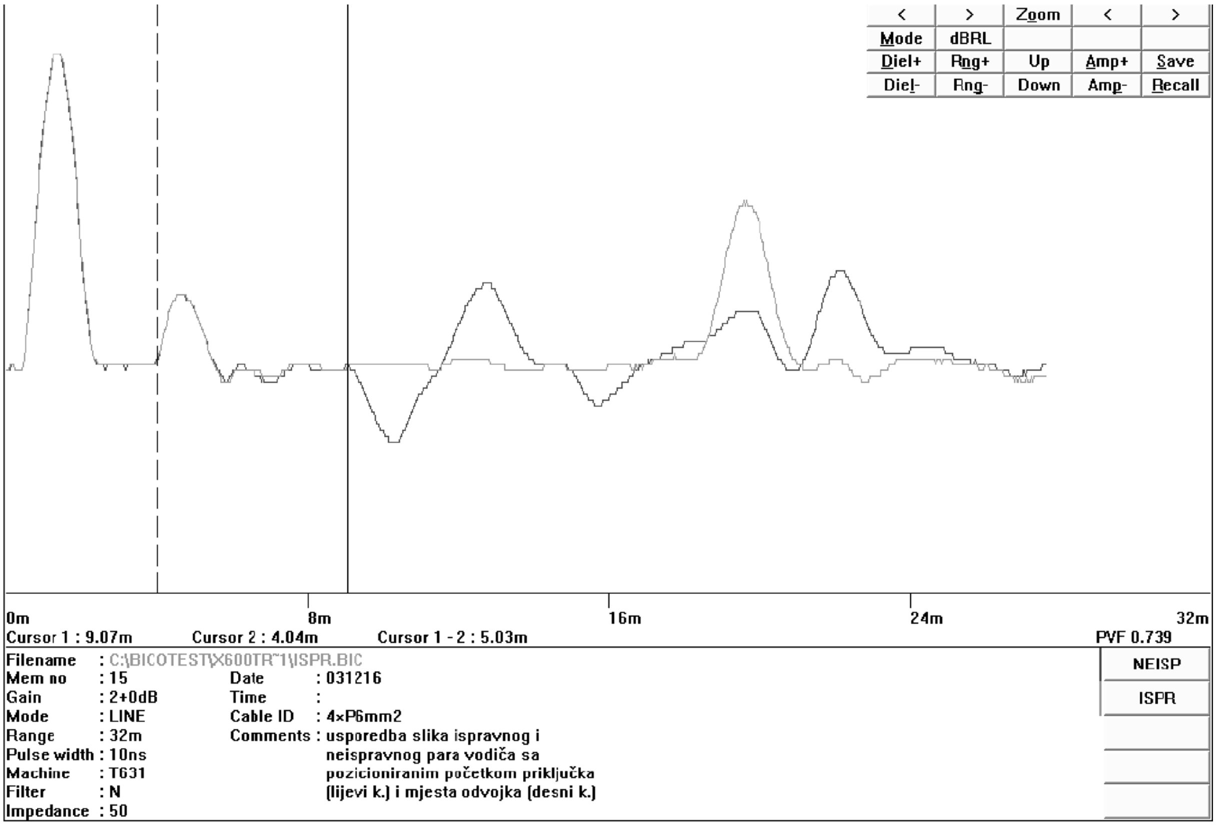

Figure 2. Response pulse of correct main power cable without illegal connection (green) and irregular main power cable with illegal connection (red)

Slika 2. Odziv ispravnog energetskog priključnog kabela bez odvojka (zeleno) i neispravnog sa odvojkom (crveno) open end. Alike, the exact point of the illegal cable along the main power cable is of high importance because of the magnitude (and energy) of the input pulse branches in two pulses at discontinuity point where magnitudes of new pulses depend on length of the illegal cable and remainder length of the main power cable ratio. If the illegal cable is longer than the remainder section of the legal connection cable, the bulk of the input pulse comes in an illegal cable. So, the response of the illegal t-junction is the same as the far end of the illegal cable and is more evident. Simultaneously, the response magnitude of the far end of the main power cable is remarkably attenuated. It is almost completely dampened if electric devices are connected (and turned on) at the end of the illegal cable due to impedance share increase.

3. The far end of the illegal connection cable opened or closed with any kind of electric device (impedance):

- open circuit – part of an electric installation usually feed beside energy registration device is turned off
- one or more electrical devices are connected on illegal cable far end and turned on

The essential difference is in wave response of the end of the tap cable: the response pulse shape of an open circuit is identical to the above presented opened far end of the main cable while the response pulse shape of the electrical devices turned on the illegal cable is similar to short connected conductors of the main power cable but of weakened magnitude. It depends on the nominal power of connected devices, in such a way that the greater the nominal power is, ghe greater the crossing pulse magnitude.

Pictures of initial wave, crossing wave and four different reflected waves of correct main power cable with lengths 3, 7, 11 and 15 meters are presented in Figure 3. There is some kind of disturbance due to type of cable (P isolated wires 4 × 6 mm^2 in protective installation tube) and impedance changes caused by a variation of conductors interdistance to each other.

Transmitted pulse response of TDR is at location of 0,4 m and crossing pulse response of junction point measurement wires – starting point of main power cable conductors is at location of 3,5 m. Response pulses of open ends of main connection cable are presented at the right hand side of above mentioned pulses. Comparing magnitudes of reflected pulse of the cable's end and initial pulse it is easy to notice attenuation of reflected pulse due to mismatching of impedances of reflectometer

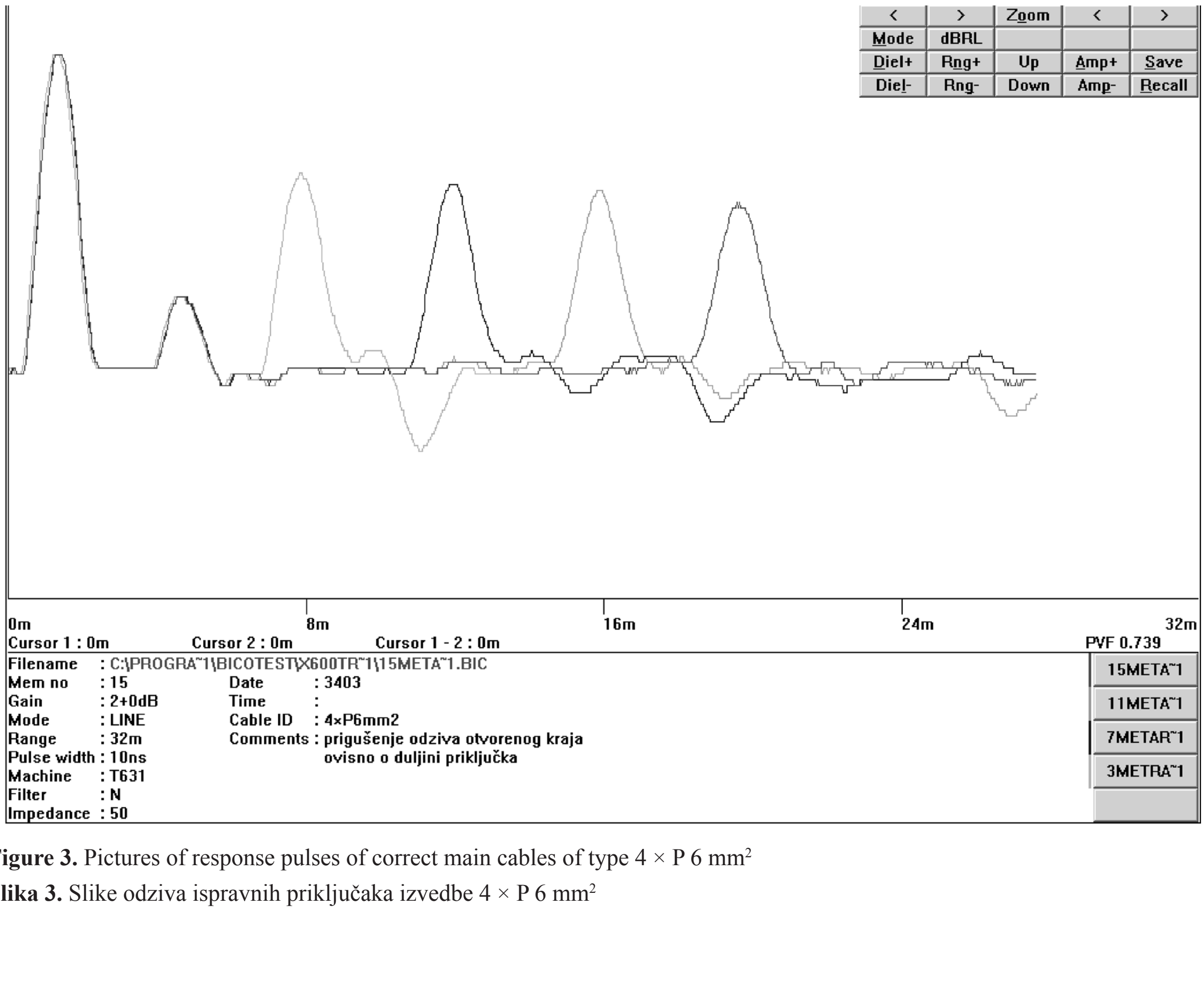

Figure 3. Pictures of response pulses of correct main cables of type 4 × P 6 mm^2

Slika 3. Slike odziva ispravnih priključaka izvedbe 4 × P 6 mm^2

and cable, due to dampening of pulse in measurement cables (25 %) and in main cable (for 10 ns width of the pulse attenuation it is 2,3 % per meter. There are also parasite responses but their locations are behind the full length of the cable.

4.2.1. Analysis of recorded pulse at main power cable with illegal connection

If a type of main connection power cable is PP00 or PP41, wave impedance is constant due to homogeneous isolation and consistent interdistances of conductors and isolation layers. Main power cable of type PP00 4×6 mm^2, total length of 8,5 m with illegal connection on 3,5 m from feeding end point is analysed at Figure 4. There are 3 response pulses of illegal connections according to length of illegal cable – 2 m, 1 m, 0,5 m opened at far end fourth one response pulse without illegal connection cable but also without an isolation on the same spot (length of the illegal cable of 0 m).

Left cursor on Figure 4 denotes starting end of the monitored cable (end where TDR is connected) and right cursor marks the exact spot of illegal connection. There is an open far end of the main power cable at distance of 11,5 m. Three above listed illegal connections are clearly visible. The fourth one, without illegal cable is also visible because of discontinuity change – eliminated isolation layers and change of conductor interdistances on the tap spot.

In the case where type of main connection power cable is P isolated wires 4 x 6 mm^2 in protective installation tube, visibility of illegal connection cable is good if illegal cables are long. In opposite, shorter lengths of illegal cables and isolation damage spots are not so easy to notice without pulse gain.

Response pulses presented in Figure 5 with P isolated conductors in protective installation tube and exact spot of the illegal junction (except in case a)) on 5 m from feeding end show following cases:

a) correct main connection power cable with length of 15 m
b) the same main power cable opened at far end with illegal cable opened on far end and its length of 3 m
c) the same main power cable short connected at far end with illegal cable opened at far end with length of 3 m
d) the same main power cable opened at far end with illegal cable (3 m) closed with electric device of nominal power 1 kW.

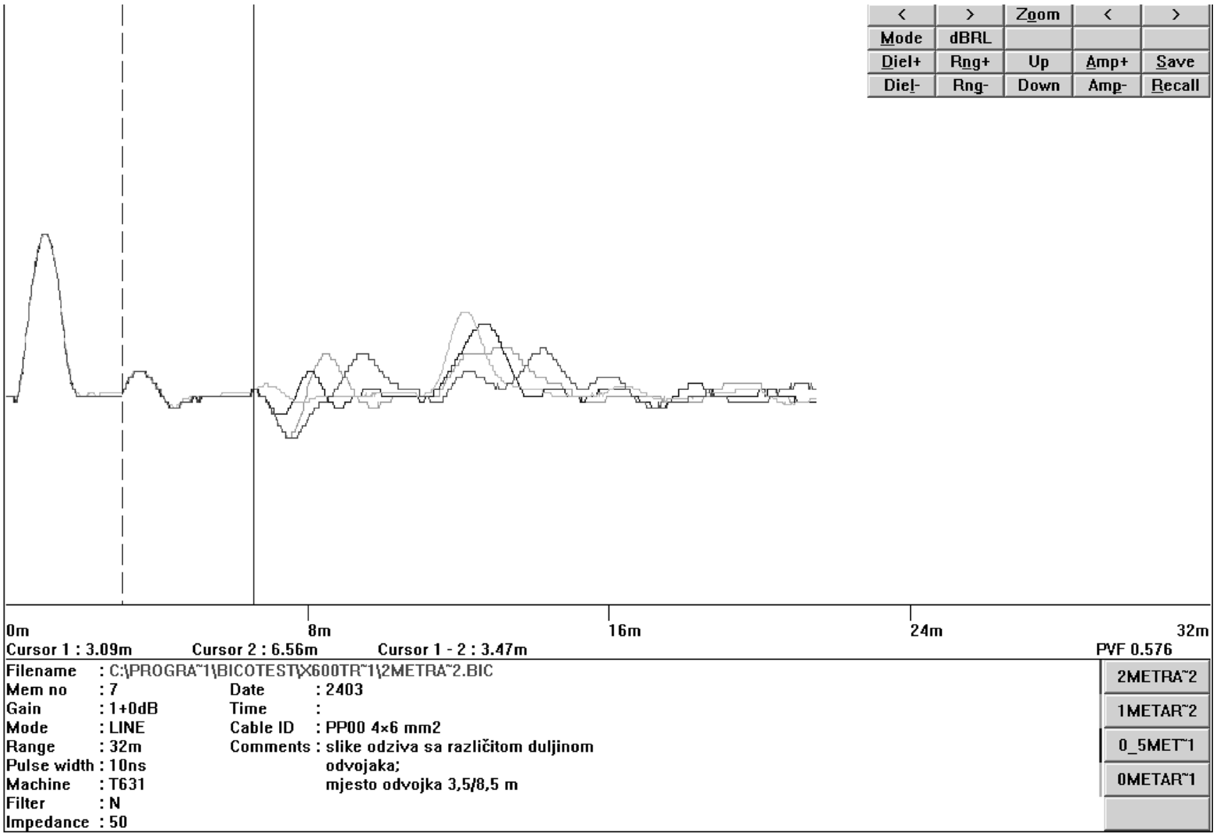

Figure 4. Pictures of response pulse of illegal cables of type PP00

Slika 4. Slike odziva priključaka s odvojkom izvedenih kabelom PP00

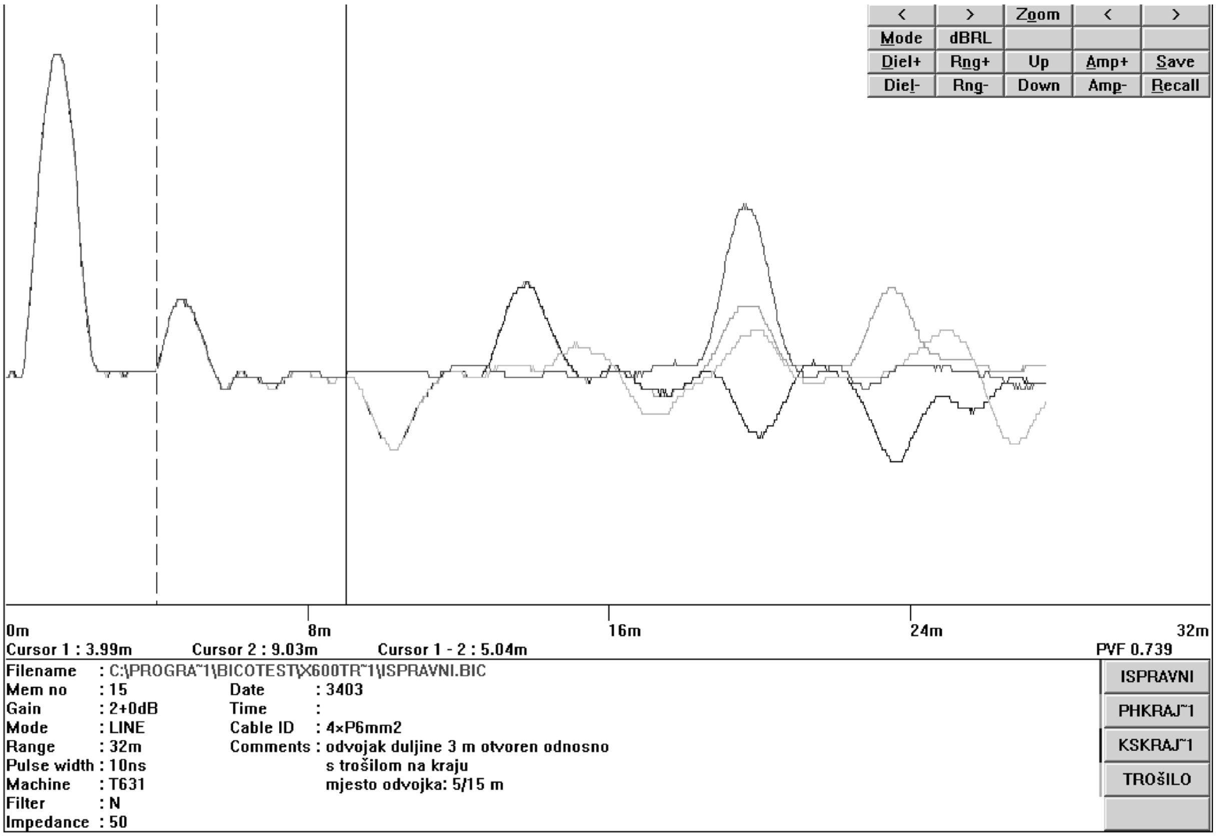

Figure 5. Pictures of response pulses of cable type 4 × P6 mm^2 in protective installation tubes

Slika 5. Slike odziva priključka s odvojkom, izvedba priključnog kabela 4 × P6 mm^2 u instalacijskim cjevima

Again, left cursor in Figure 5 marks one end of the monitored cable (end where TDR is connected) and right cursor denotes t-junction location. There is the far end of the main power cable at a distance of 18,5 m and the exact spot of illegal junction at a distance of 11,5 m. It is interesting to note:

- attenuation of response pulse from far end of main power cable is the same in both cases – open end and short connected end due to branching pulse into illegal cable;
- if there is a connected electric device (and also turned on) at illegal cable, reflected wave from opened end of the main power cable weakens (magnitude decrease depends on nominal load of the electric device.

4.2.2. Waves difference method

It is very simple to determine if there is an illegal connection on main power cable. The method consists of the following steps:

- record the reflectometer picture of response pulse of main power cable with short connected conductors and store it in TDR memory,
- record the reflectometer picture of response pulse of the main power cable with opened far end,
- choose function wave difference between both cases (opened and short connected far end).

If the main power cable is in a correct state, the picture looks like a straight line from TDR and response pulse of the far end of twice magnitude. In the case where an illegal junction exists, the response pulse at the far end is attenuated and extorted.

Subtraction of reflected waves presented in Figure 6 shows the main power cable, length 14 m and illegal connection, length of 1 m at half of main cable. In Figures 7 and 8, the same main power cable is analyzed but with an illegal cable, length of 3 m and 6 m. Notable changes in magnitude and in shape of the reflected wave can be clearly seen.

4.2.3. An example of detected illegal connection

Recorded response pulses of real main power cable performed by 4 × P 10 mm^2 wires in isolation tube, length of 18,8 m with detected illegal connection are given in Figure 9.

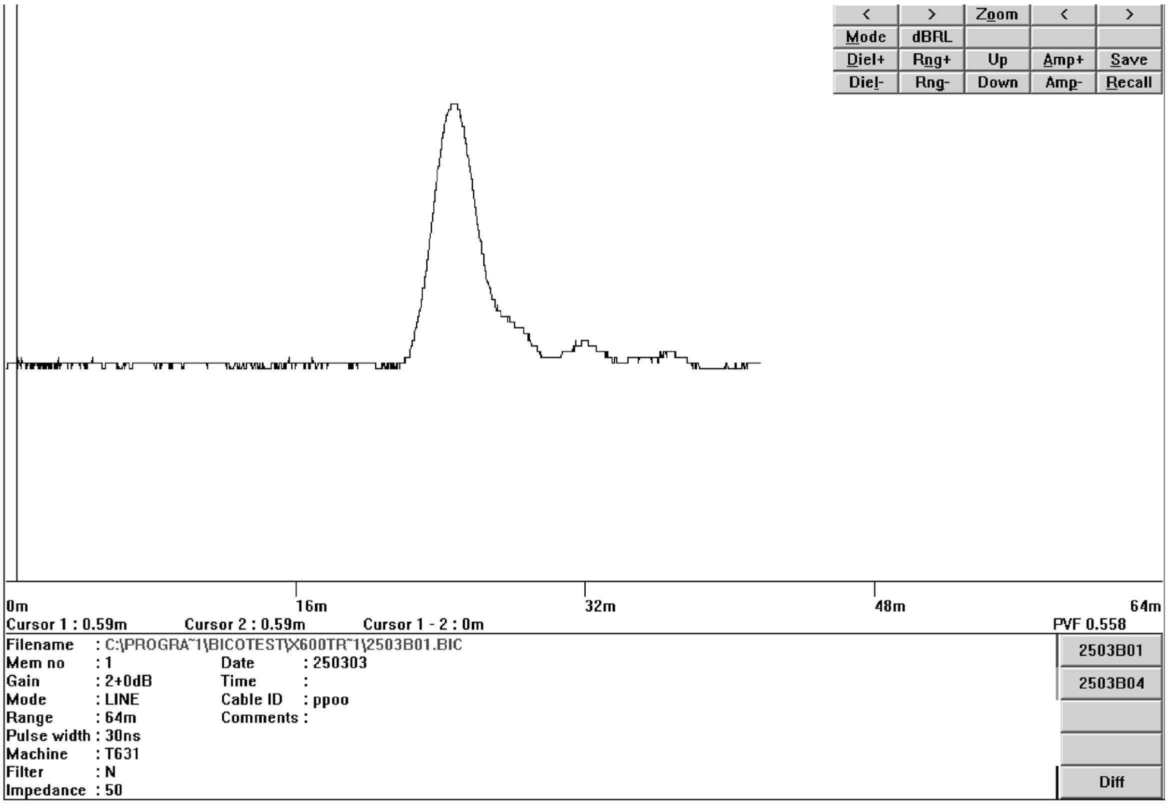

Figure 6. Picture of reflected wave at illegal connection, length of 1 m, main power cable length of 14 m

Slika 6. Slika reflektiranog vala na ilegalnom odvojku duljine 1 m, glavni energetski kabel duljine 14 m

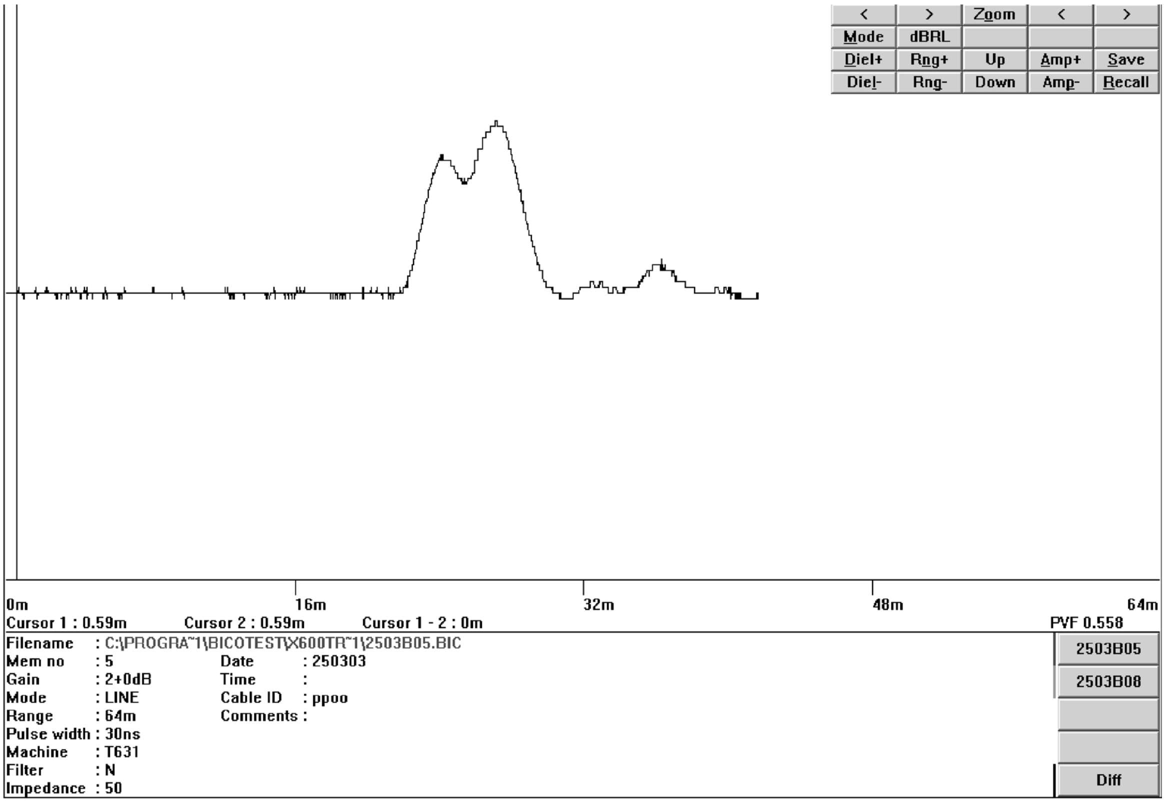

Figure 7. Picture of reflected wave at illegal connection, length of 3 m, main power cable length of 14 m

Slika 7. Slika reflektiranog vala na ilegalnom odvojku duljine 3 m, glavni energetski kabel duljine 14 m

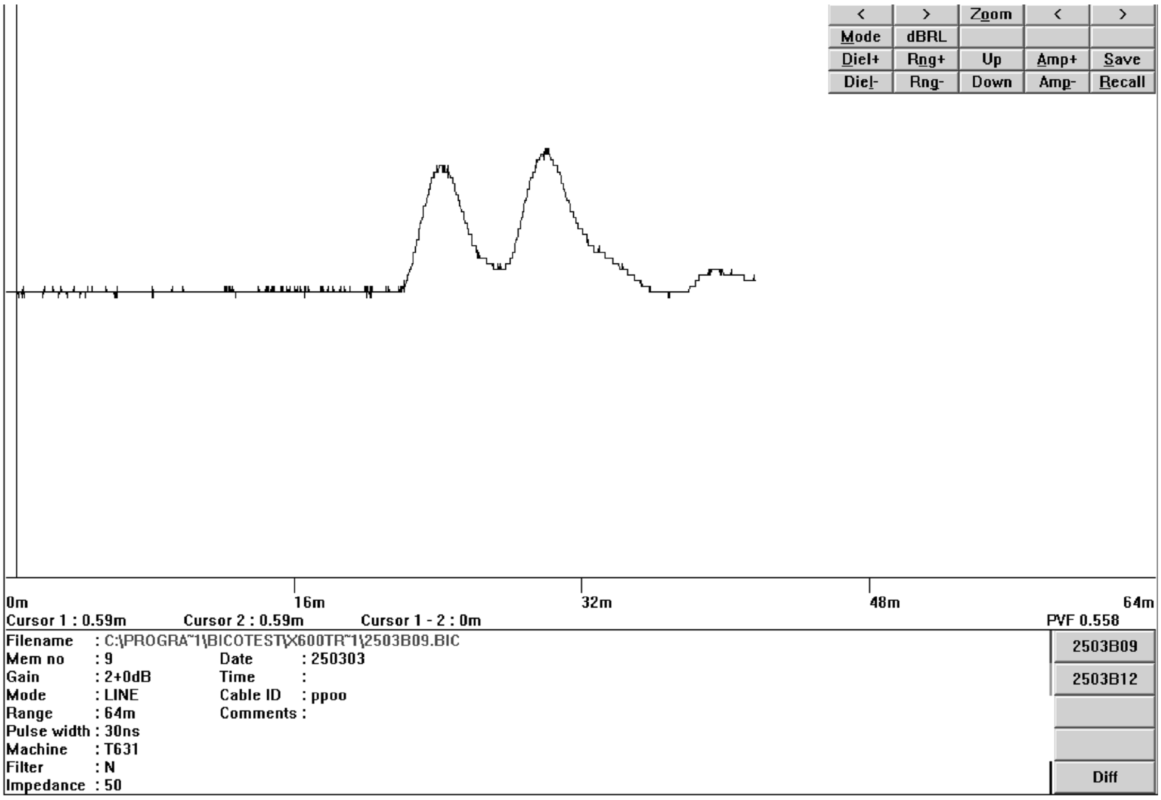

Figure 8. Picture of reflected wave at illegal connection, length of 6 m, main power cable length of 14 m
Slika 8. Slika reflektiranog vala na ilegalnom odvojku duljine 6 m, glavni energetski kabel duljine 14 m

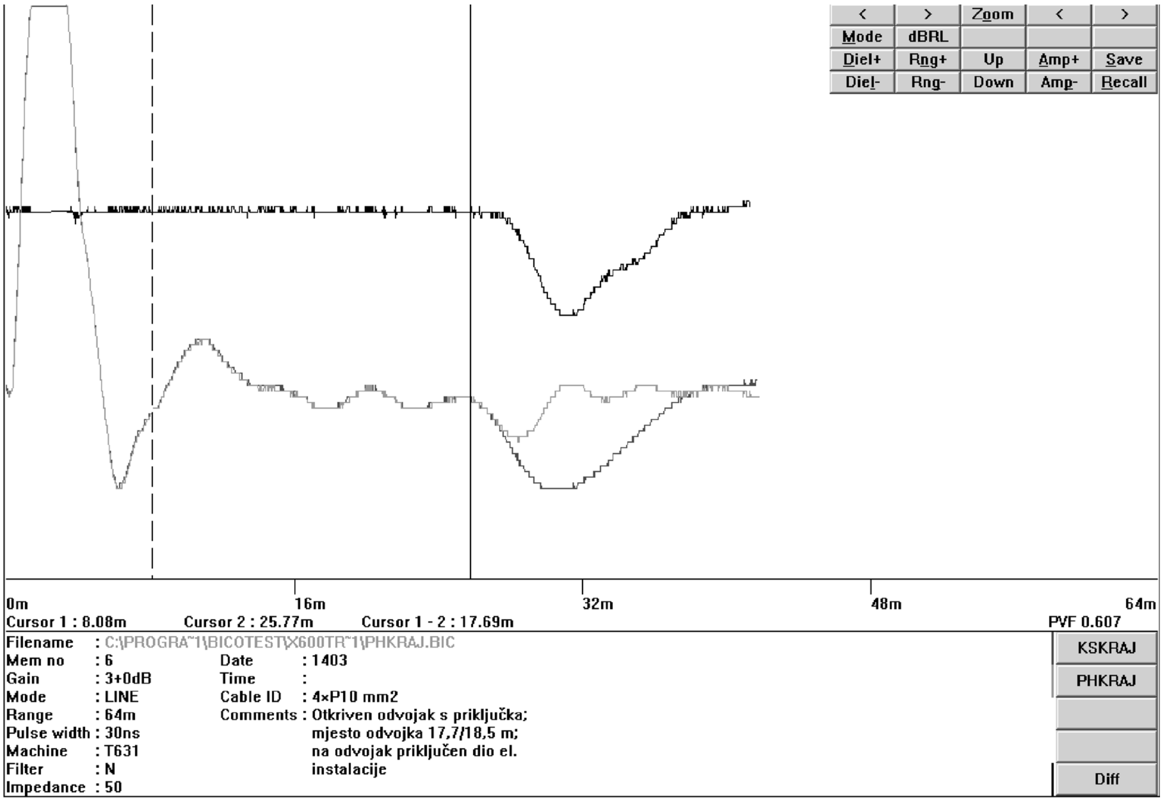

Figure 9. Picture of response pulse of main power cable with detected illegal connection
Slika 9. Slika odziva priključka s otkrivenim odvojkom

Here, the reflectometer is connected at the monitored cable with additional cable, length of 5 m (left cursor). Real location of illegal connection is at 1,1 m from the far end of the main cable (right cursor). There is a reflected wave of opened far end (green line), the same wave of short connected far end (red line) and difference of former two pulses (black line). At first glance, it is obvious that illegal connection exists because of unexpected picture with opposite sign and extorted shape of the wave due to power load at end of the illegal cable. The difference of waves for correct cable is double magnitude of response pulse of cable with open far end. Here, the exact place of illegal connection is also easy to determine.

4.3. Testing the section of live main power cable

This option is applied in case of:

- control of the first part of the main power cable from consumer's fuses to overhead low voltage network (mounted through private ownership),
- control of the first part of the underground main power cable from consumer's fuses to connection with "T" joint on underground low voltage network (placed underground).

Here, it is not expected to get response pulses of opened and/or short connected conductors of the far end of the cable but response pulses of the t-junction of cable on low voltage network. Advisable method in detecting eventual existing illegal cables is a systematic and detailed section-by-section review of main power cable using gain and zoom functions of measurement device.

Transmitted and reflected wave of correct main power cable X00/0 4 × 16 mm^2 from house fuses to junction to overhead low voltage distribution network, total length of 30 meters is presented in Figure 10. The first 7 m is through walls of consumer's house. Measurement cable between reflectometer and tested cable, length of 5 m is used. Left screen the cursor denotes place of main fuses. The far end of tested cable (connection to overhead network) is tracked by right screen cursor. There are two waves in Figure 10: wave width for green line is 10 ns and for red one is 30 ns. Detailed analysis shows that there is no illegal cable on tested main power cable.

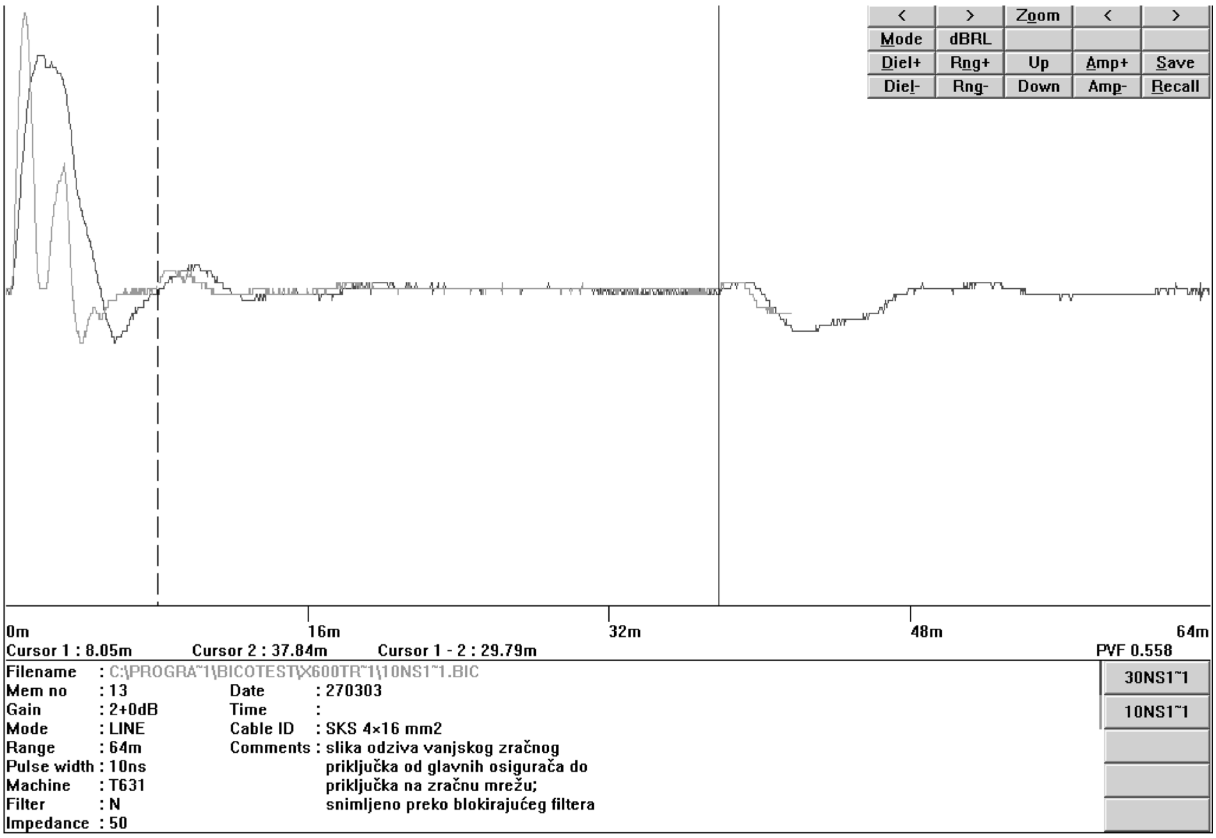

Figure 10. Picture of response pulse of live main cable (main fuses – overhead network)

Slika 10. Slika odziva priključka pod naponom (glavni osigurači – zračna mreža)

5. Conclusion

The main idea of the research was to improve financial benefit of power system and electricity supply, to reduce commercial losses in such a way as to identify and enable more detailed measurement procedure in distribution networks. Developed method using TDR for described purpose is based on performed research for the first time, according to all scientific literature available to authors.

The goal of this paper is to emphasize the importance of improving effectiveness in power distribution system operation. Total losses consist of technical end commercial losses. There are many well-known methods for reducing technical losses, but commercial losses (theft of electricity by some person of questionable reputation) are rarely analyzed in detail. Here, proposed measurement procedure is recommended for systematic use along the power liner of low voltage distribution network. It is easy to detect all illegal junctions and its location on main house power cable. Duration of testing measurement procedure is about 30 minutes per main house power cable, half of time for preparation activities (disconnect cable, remove and put the control lead) and the other half for measurement. Two electricians are sufficient as a crew to do the described measurement. Transmitted and reflected waves of main power cables, recorded in TDR internal memory, are easily memorized on PC and analyzed, anytime needed. It is good to get a record of each connection cable and to store in the data base as fingerprint for later analysis and comparison with new measured response wave in repeated controlling of the main power cable.

During research, hundreds of measurements were performed with variation of input parameters (cable types, closing impedance and distance between illegal connection point and end of cable) due to termination of expected responses for different cases and to prove modelled influence factors. Today, proposed measurement procedure for main power cable inspection and simultaneous detection of exact spot of eventual existing illegal junction is already used in Croatian Power Company.

Furthermore, proposed measurement procedure for commercial reduction losses in power distribution system makes important benefits in increasing customer power quality, especially connected to voltage conditions at the end of the power line (according to EN 50160), which is of high importance in emerging electricity market conditions and a next step in future research.

REFERENCES

[1] STOJKOV, M.; TRUPINIĆ, K.; NIKOLOVSKI, S.: *Technical Losses in Power Distribution Network,* Proceedings of the 13th IEEE Mediterranean Electrotechnical Conference, MELECON, Malaga, Spain, May 16-19, (2006), Power resources and Systems, 1048-1051.

[2] STOJKOV, M.; TRUPINIĆ, K.; POLETO, D.: *Reduction of Power and Voltage Losses in Low Voltage Networks by Reactive Power Compensating*, The 18th International Conference on Electricity Distribution, CIRED, Turin, Italia, 6-9 June (2005), Session No 5 – Power Distribution System Development.

[3] PAVIĆ, A.; STOJKOV, M.; TRUPINIĆ, K.: *Illegal Connection Location on Main Power Cable*, Proceedings of the 12th IEEE Mediterranean Electrotechnical Conference, MELECON, Dubrovnik, Croatia, May 12-15, (2004), Vol. III, 983-986.

[4] BEGO, V.: *Mjerenja u elektrotehnici*, Tehnička knjiga, Zagreb, Croatia, (1990), 87-105.

[5] BICOTEST LIMITED, T631 TDR operating manual, 2000.

[6] TRUPINIĆ, K.; STOJKOV, M.; POLETO, D.: *Reduction of Non-technical Losses Based on Time Domain Reflectometer (TDR) Principles and Function*, The 18th International Conference on Electricity Distribution, CIRED, Turin, Italia, 6-9 June (2005), Session No 5 – Power Distribution System Development.