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PROCEDURE FOR DETERMINATION OF HARMONIC DISTORTION ALONG THE DISTRIBUTION NETWORK

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Original scientific paper

This paper underlines the importance of permanent power quality measures in distribution network and proposes the interval and event (change in topology) based time schedule of measurements in depth of the network. Some nodes do not need to be measured during 7 days according to EN 50160 to realize that there are great problems to solve in a new technical resolution. Similar to the trend of entropy, true harmonic distortion (THD) in distribution power system is expected to increment, so - momentary measures are sufficient to mark subparts of the power system with unsatisfactory level of power quality. The most important problem to solve is to mark the consumer's generated harmonic distortion. Importance and benefit of the proposed method is to save the time needed to name causes of disturbances (consumer or device) and to anticipate the repairing of power quality. A new flow-chart is suggested for recognition of the consumer THD generation amount. Also, it leads to better technical or managing decision making during maintenance and investment planning activities. Further results of systematic planned measures that need to be done along the distribution power network, will enable global recognition of THD causes in network and simultaneously give exact solutions.

Key words: *consumer, harmonic distortion, power quality, source recognition*

Postupak za određivanje harmonične distorzije uzduž distribucijske mreže

Izvorni znanstveni članak

Ovaj članak naglašava važnost stalnog mjerenja kvalitete električne energije u distribucijskoj mreži i predlaže vremenski raspored mjerenja po dubini mreže određen vremenskim intervalom ili događajem (promjena u topologiji mreže). Neki čvorovi ne moraju biti stalno mjereni tijekom 7 dana prema normi EN 50160 da se zaključi da postoje veliki problemi vezani za kvalitetu za novo stanje mreže koje treba riješiti. Slično kao ponašanje entropije, za udio harmoničnog izobličenja (THD-a) u distribucijskoj mreži očekuje se da isključivo raste tako da su trenutačna mjerenja dovoljna da se označe dijelovi distribucijskog sustava koji nemaju zadovoljavajuću razinu kvalitete. Najvažniji problem kojega treba riješiti je odrediti kupca koji proizvodi harmonično izobličenje. Važnost i korisnost predložene metode je ušteda vremena za određivanje uzroka poremećaja (kupca ili uređaja) kao i za predviđanje načina za poboljšanje kvalitete električne energije. Predložen je novi dijagram toka za prepoznavanje količine proizvedenog THD-a od strane određenog kupca. Također, uporabom ove nove metode mjerenja kvalitete olakšava se donošenje odluka u tehničkom i organizacijskom segmentu tijekom aktivnosti održavanja i planiranja investicija. Daljnji rezultati sistematski planiranih mjerenja uzduž distribucijske mreže omogućit će globalno prepoznavanje veličine uzroka harmoničnog izobličenja i istovremeno dati određena rješenja.

Ključne riječi: *kupac, harmonična distorzija, kvaliteta električne energije, prepoznavanje izvora*

1 Introduction
Uvod

Usually, harmonics are the base point when engineers start to analyze waveform distortion. Frequencies of these voltage and current waveforms are integer multipliers of the base frequency of power system (50 Hz or 60 Hz). If it is not the case then these are named as intermediate harmonics.

The sinusoidal waveforms of voltage characterize the ideal power system with the highest clarity of base frequency. In technical means, higher harmonics source generated appearance is caused by an imperfect stator roller line and uneven coil configuration, by power transformers magnetizing current contained and by power transformers core saturation emerging. All the listed causes are generated by reactive power compensating static devices. Part of the total harmonic distortion of source-generated appearance (distribution power transformers or generators) is neglected.

Harmonic and intermediate harmonic distortions are primarily caused by equipment with nonlinear voltage and current characteristics. Non-sinusoidal currents appear if a load current is not linearly related with enforced voltage. In a simple circuit, which is composed of linear elements – resistor, inductance and capacitance, electric current is completely related to enforce sinusoidal voltage (of base frequency), so sinusoidal voltage responds to sinusoidal current. The load characteristic is the ratio between the enforced voltage and the responding load current. When the load is reactive, then there is a phase shift between current wave form and voltage wave form, power factor is decreased, yet it is possible the circuit is still linear. As an example, usual characteristic of simple capacitive – smoothed full wave (diode bridge) rectifier is like simple power supply switch mode entry. In this case, current flows only when enforced voltage exceeds the capacity voltage, in fact close to the peak sinusoidal wave form voltage value, and that shows the load characteristic form. The load characteristic (wave current form as well) is very complex in reality – asymmetry, hysteresis, inflexions and trends are variable with load value in real life.

Here, a new approach is presented used for consumers recognition caused by harmonic distortion of waveform on the electricity distribution connection bus. The amount of harmonic distortion level of brand new consumer can be easily determined by harmonic distortion measures in the same point of network before and after connection of new consumer.

But to check existent electricity consumer is hard to perform because of the consumer's need for continual electricity supply.

2 Harmonic distortion
Harmonična distorzija

Consumers (routers, converters), work as rectifiers (converting an alternate current into a direct current), or as transducers (converting a direct current into an alternate current), which use distorted current from the power system, and due to their characteristics are the widest range of higher generators' harmonics.

Figures 1 and 2, show FLUKE 434 PQA instrument recorded current wave form and voltage wave form on an electric installation box which feeds PC with LCD monitor and laser printer. Harmonics content graph and precedent current graph is on the right.

The most distinctive is the third harmonics, but the frequencies of the fifth, the seventh, the ninth and other higher harmonics are also existent. THD current in the measuring moment is 39,7 %. It is noticeable nonlinear modern consumer's cumulative effect on the electric power quality and because of its low power consumption (in this case app. 0,2 kW) alike with no influence, but with wide range use is not negligible in that sense.

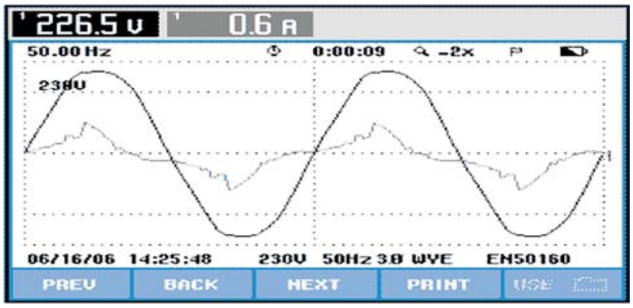

Figure 1 *Current and voltage waveform*
Slika 1. *Valni oblik struje i napona*

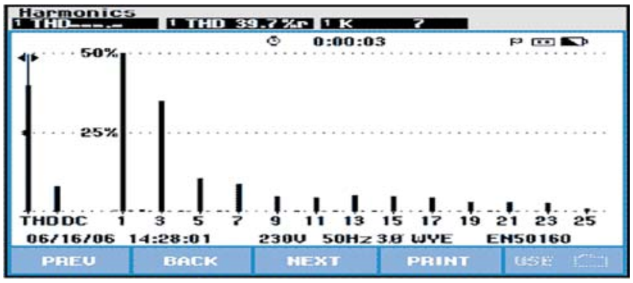

Figure 2 *Current harmonics content graph*
Slika 2. *Raspodjela strujnih harmonika*

According to the Fourier analysis, every periodical waveform can be divided into a basic sinusoidal frequency wave and total of sinusoidal harmonics frequency wave amount.

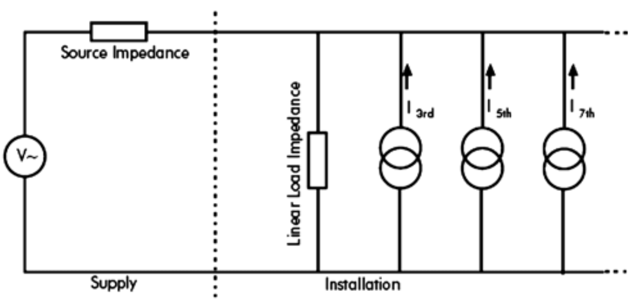

Figure 3 *Equivalent non-linear load circuit*
Slika 3. *Nadomjesna shema nelinearnog opterećenja*

The equivalent nonlinear load circle is shown in Figure 3. It can be modelled like a linear load with more current parallel sources, one source for each harmonics frequency. According to the superposition theory, base frequency voltage source causes power short-circuit for higher harmonics frequency. So the understanding of current harmonics as current sources in combination with internal sources impedances and network impedances makes the first step to get expected response in a form of distorted wave voltage form and to do corrective actions on linear loads of harmonic distortion supply.

Higher harmonics, depending on their order, create symmetrical three phase systems of direct, invert and zero components. Direct system current harmonics causes reciprocal voltage decrease on direct distribution system branches impedances, with regard to an impendence matching with designated harmonics frequency.

Expressions for three voltage phases for N^{th} harmonic:

$$\begin{aligned} \overline{V}_{1N} &= V_N \cdot e^{jN\omega t}, \\ \overline{V}_{2N} &= V_N \cdot e^{jN\cdot(\omega t - \frac{2\pi}{3})}, \\ \overline{V}_{3N} &= V_N \cdot e^{jN\cdot(\omega t - \frac{4\pi}{3})}. \end{aligned} \tag{1}$$

For N=1 the basic harmonic is created. The basic harmonic creates direct component (d), second harmonic (N=2) inverses component (i), and third harmonic (N=3) creates zero component (0) of three-phased system.

In general, direct system is created by harmonics range:

$N = 3n + 1$ for $(n = 0, 1, 2...)$,

Inverse system created by harmonics range:

$N = 3n - 1$ for $(n = 0, 1, 2...)$,

and zero system created by harmonics range:

$N = 3n$ for $(n = 0, 1, 2...)$.

Harmonics range can be divided in:

a) Even harmonics (N is even number). Even current harmonics (and voltage harmonics dependant impedance) are caused solely by the distribution system interference, which is not identically manifested for both half periods of basic wave. Seldom manifested (e.g. caused by half wave rectifier) and seldom observed, although these harmonics are resulting worse faults because of direct current component content which shifts a transformer core to saturation.
b) All harmonics with frequency multiplier are divisible by 3. They form the zero system and that is the reason they outstand from others. Most often, they are created during saturated iron cores magnetizing, where the third harmonic is the most dominant. Harmonic currents of that group are circut spots where the zero system is connected with the power system zero point. Crucial role in that process is plagued by a transformer coil connection triangular in shape, especially because it enables harmonics N=3 circulation.
c) The other harmonics with uneven frequency multipliers create direct or indirect modelled system. These harmonics are the most analyzed ones.

Each N^{th} frequency multiplier harmonic forms an ideal sinusoidal wave of frequency $N \cdot f$. Harmonics have different magnitudes (with increasing N, magnitude sharply drops). In every case, the basic harmonic (N = 1, f = 50 Hz) is existent and that is the one with the highest magnitude.

Addition of all simultaneously existing harmonics (e.g. voltages) during the observed period in phase 1 result (if direct component not existent) in a terminal curve of momentary voltage value:

$$U_1 = \mathrm{Re}\cdot \sum_{N=1}^{\infty} \sqrt{2} \cdot U_N \cdot e^{j(N\omega t + \varphi N)}, \quad (2)$$

where is:
N – harmonics' frequency multiplier
$\omega = 2\pi f$ – basic harmonics' circular frequency
U_N – effective value of N^{th} harmonics
Φ_N – phase angle of N^{th} harmonics relatively to the main axis.

The curve U_1 is periodical, deviates from an ideal sinusoid:

$$U_1 = \mathrm{Re}\cdot \sum_{N=1}^{\infty} \sqrt{2} \cdot U_N \cdot e^{j(\omega t + \varphi)}. \quad (3)$$

That is a distorted sinusoid, and measure for the distortion is the distortion factor defined by expression:

$$D = \frac{\sqrt{\sum_{N=2}^{\infty} U_N^2}}{U_1}. \quad (4)$$

That factor contains all of the harmonics independently of unequal interference intensity of different harmonic groups.

Harmonics' deviation influence in the power networks does not have to be initially visible, but it can have serious long term consequences in. The most important are:

- Loading of consumers' electrical installation and power system elements by voltages and currents frequencies not designed for,
- Increased heating of transformers and increased heating of neutral conductors caused by higher current harmonics whose frequency is the multiplier of number 3. Increased level of the 3rd harmonics in the neutral conductor can cause fire, because the neutral conductor is usually not overload protected.
- Increased transformer heating caused by higher harmonics, as well as saturation effects in the core causing the transformers', loadable power decreasing below the nominal power in consumers and power distribution plants.

There are interesting appearances and consequences:

- Higher harmonic appearance in the power system can cause interferences on telecommunication lines,
- Bad power factor interconnected with nonlinear loads is responsible for significant current increase, through power system and consumer electrical installation, and significant financial losses increase caused by the power losses,
- Equipment and electrical device depreciation caused by e.g. insulation overload increased by an additional heating.

If non-linear loads increase in the power distribution system, voltage distortion increases in direction from source to end-user, due to electrical circuit impedance. Loads cause current distortion in the majority of the cases. If few electrical apparatuses are connected on the same connecting lead, harmonics current of one electrical device producing voltage distortion can influence the other electrical apparatus' operation, causing current harmonics of individual electrical apparatus imprint in the electrical power system norms to rise. Current harmonics of the same frequencies from different sources are vector added. In Great Britain it is considered that 5th harmonic is with the highest peak values of high voltage, with 2,5 % and 3,0 % values on the some locations. The 5th harmonic presents the highest average harmonics value in most of the cases, which is proved by many geographical and periodical consistent measurements.

3 Existent consumer's feedback
Postojeća povratna informacija potrošača

The electricity supply company performs power quality measuring on network bus - connection point in the following cases:

- Other consumers' complaints on power quality,
- Determining poor power quality by planned network measuring,
- Significant connection peak power in connection point, which is defined by the following condition:
  - S_{3PK}/S_P < 1000 for consumers connected at middle voltage network,
  - S_{3PK}/S_P < 150 for consumers connected at low voltage network,

  where S_{3PK} is short connection point power, and S_P consumers' connection peak power,
- Existence of a number of the nonlinear electrical apparatuses that can be seen from the consumer's design of electric device documentation.

3.1 Distortion of voltage wave
Izobličenje vala napona

Increase of the *THD* of voltage wave on connection point of network caused by nonlinear load depends on:

- Participation of nonlinear load shown by total distorted harmonics of electrical devices load – *THDI*.
- Value of the total electrical devices load – power *I*,
- The distribution network power in a connection point expressed with the network impedance *Z* or with three pole short connection power S_{3PK}.

$$\Delta THDU = f(I, THDI, Z) \quad (5)$$

Or in other way:

$$\Delta THDU = k \cdot I \cdot THDI \cdot Z \quad (6)$$

Where is:
Δ *THDU* - Value of additional increase of the total distorted harmonic wave (power) voltage caused by the nonlinear electrical devices' load,
I - Total power of consumer's electrical devices,

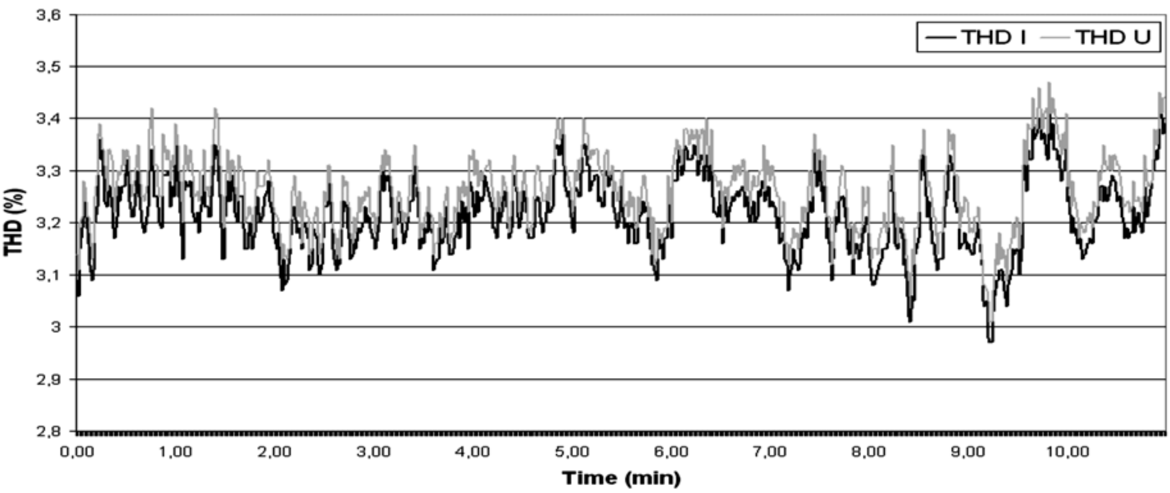

Figure 4 *Period diagram THDU and THDI for pure linear load*
Slika 4. *Vremenski dijagram THDU i THDI za linearni teret*

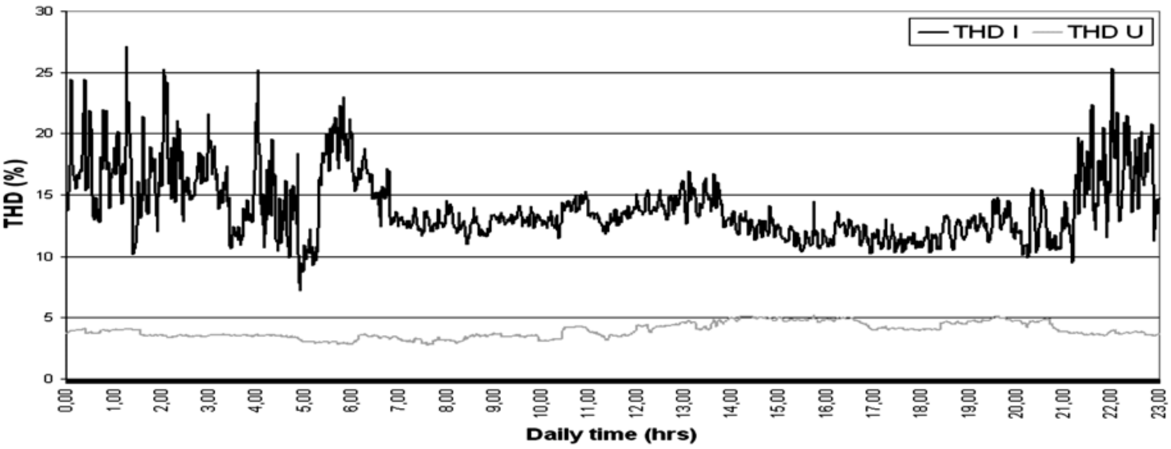

Figure 5 *Period diagram THDU and THDI for non-linear load*
Slika 5. *Vremenski dijagram THDU i THDI za nelinearni teret*

THDI - Total value of consumers' electrical devices distorted harmonics,
Z - Power network impedance in the connection point,
k - Relational coefficient used to determine nonlinear load influence on harmonics distortion voltage supply increment in exact impedance network point.

Figure 4 contains interrelated period diagram *THDU* and *THDI* for pure linear load. *THDI* is completely of the same shape as *THDU*, because *THDI* is generated by *THDU* existence in electricity supply network. Difference in the shape between momentary values of *THDI* and *THDU* is caused exclusively by nonlinear consumer's electrical devices on connection point period diagram where the measurement is recorded. But values of total harmonic distortion itself do not contain nonlinear load value, so multiplying *THDI* by the total load *I*, produces quantitative value of consumer's' nonlinear devices load influence on *THD* load increment in electricity network.

Figure 6 presents essential objective the paper deals with – determining $\Delta THDU$ based on measured $I \cdot THDI$ and *Z*. On any bus of the electricity network unknown relation variable *k*, the following approach can be used. Determining $\Delta THDU$ caused by nonlinear load on the power system connection point is conveyed by the network impedance change of chosen point.

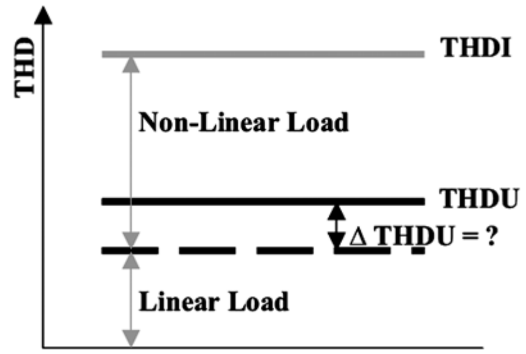

Figure 6 *Determining ΔTHDU based on I·THDI and Z*
Slika 6. *Određivanje ΔTHDU preko I·THDI i Z*

3.2
Power system impedance change (two points)
Promjena impendancije električnog energetskog sustava (dvije točke)

At the same time, measurements of power quality and consumers' load parameters are made on two different power system buses with different impedances.
As a simple example, Figure 7 describes power transformer simultaneous measurement on middle and low voltage side the consumer is getting electricity from. The difference of $THDU_{LV}$ values according to $THDU_{MV}$ value is generated by:

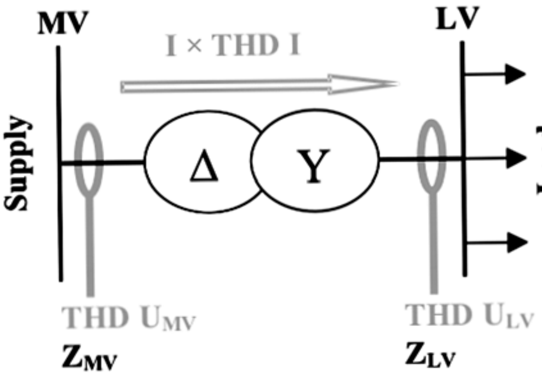

Figure 7 Simultaneous measurement on MV and LV side
Slika 7. Istovremeno mjerenje na SN i NN strani

- Absence of $3n$ LV harmonics to the MV side of transformer caused by triangle winding form on the MV side,
- *THD* increment due to an impedance increase from Z_{MV} to Z_{LV}.

By the last mentioned cause and inserting in the relations (7) and (8):

$$\Delta\ THD\ U_{LV} = \Delta\ THD\ U_{\Delta Z} \cdot \frac{Z_{LV}}{\Delta Z} \tag{7}$$

$$\Delta\ THD\ U_{MV} = \Delta\ THD\ U_{\Delta Z} \cdot \frac{Z_{MV}}{\Delta Z} \tag{8}$$

where is:
$\Delta\ THDU_{LV}$ - Value of additional *THD* voltage increment generated by nonlinear consumers' load on LV point,
$\Delta\ THDU_{MV}$ - Value of additional *THD* voltage increment generated by nonlinear consumers' load on MV point,
$\Delta\ THDU_{\Delta Z}$ - Value of additional *THD* voltage increment generated by nonlinear consumers' load on power Transformer impedance ΔZ,
Z_{LV} - Network impedance on LV point,
Z_{MV} - Network impedance on MV point,
ΔZ - Transformer impedance difference Z_{LV} and Z_{MV}.

3.3 Power system impedance dynamic change
Dinamička promjena impedancije elektičnog energetskog sustava

By change of the power system impedance Z in connection point, total harmonic distortion level is changed too. If the power system impedance Z decreases, total harmonic distortion of voltage waveform decreases too. In analogy, if the power system impedance Z increases, total harmonic distortion of voltage waveform increases too.

Amount of the change of total harmonic distortion of voltage is caused by nonlinear load $I{\cdot}THDI$ of the particular consumer.

So with impedances Z_1 and Z_2:

$$(\Delta\ THDU)_1 = k \cdot I \cdot THDI \cdot Z_1 \tag{9}$$

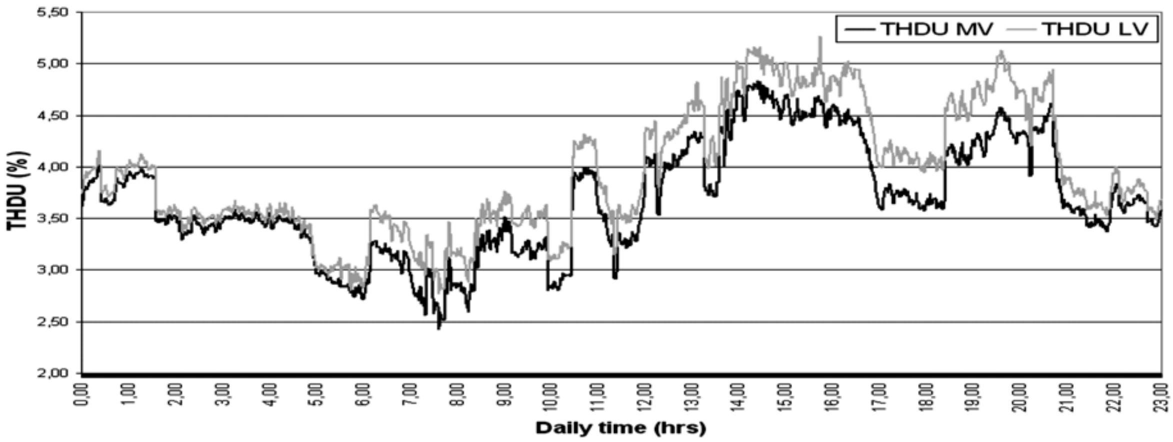

Figure 8 Simultaneous period diagram recorded $THDU_{MV}$ and $THDU_{LV}$
Slika 8. Vremenski dijagram istovremeno snimljenih $THDU_{SN}$ i $THDU_{NN}$

$$(\Delta\ THDU)_2 = k{\cdot}I{\cdot}THDI{\cdot}Z_2 \tag{10}$$

Ratio of changes on *THDU* is:

$$\frac{(\Delta\ THDU)_1}{(\Delta\ THDU)_2} = \frac{Z_1}{Z_2} \tag{11}$$

There are several possibilities for impedances Z_1 and Z_2 measuring in a consumer connection point - in different moments of maximum and minimum non linear load - $(I{\cdot}THDI)_{1max}$, $(I{\cdot}THDI)_{1min}$, $(I{\cdot}THDI)_{2max}$ and $(I{\cdot}THDI)_{2min}$. All measured $I{\cdot}THDI$ values are determined by equation (6), and with given equation (11) a system is solved.

An example for the network's impedance change is the connecting and disconnecting of one power transformer which is in parallel line with one or more other transformers, as shown in Figure 9.

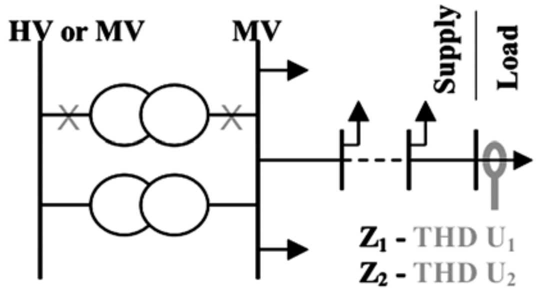

Figure 9 Network impedance periodic changes
Slika 9. Promjena impedancije mreže

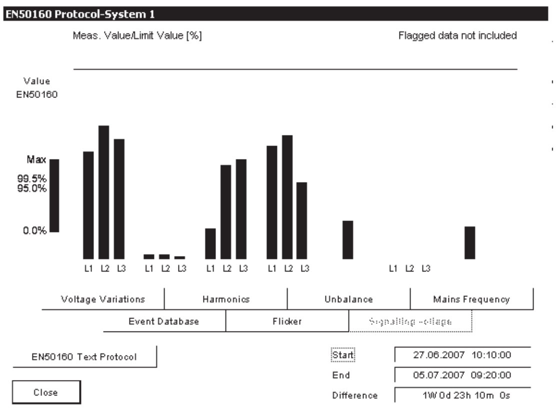

Figure 10 *Summary power quality indices at 110 kV voltage level at MT1*
Slika 10. *Sumarni pokazatelji kvalitete električne energije na 110 kV naponskoj razini (MT1)*

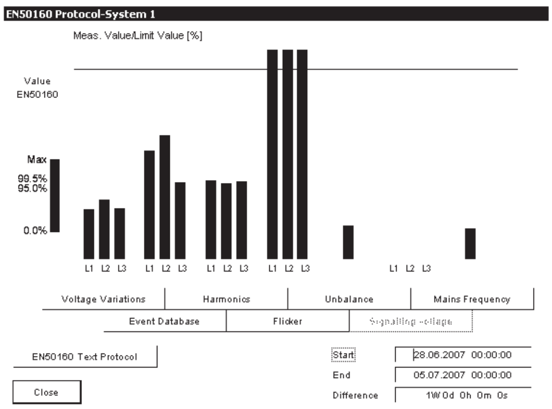

Figure 11 *Summary power quality indices at 10 kV voltage level at MT4*
Slika 11. *Sumarni pokazatelji kvalitete električne energije na 10 kV naponskoj razini (MT4)*

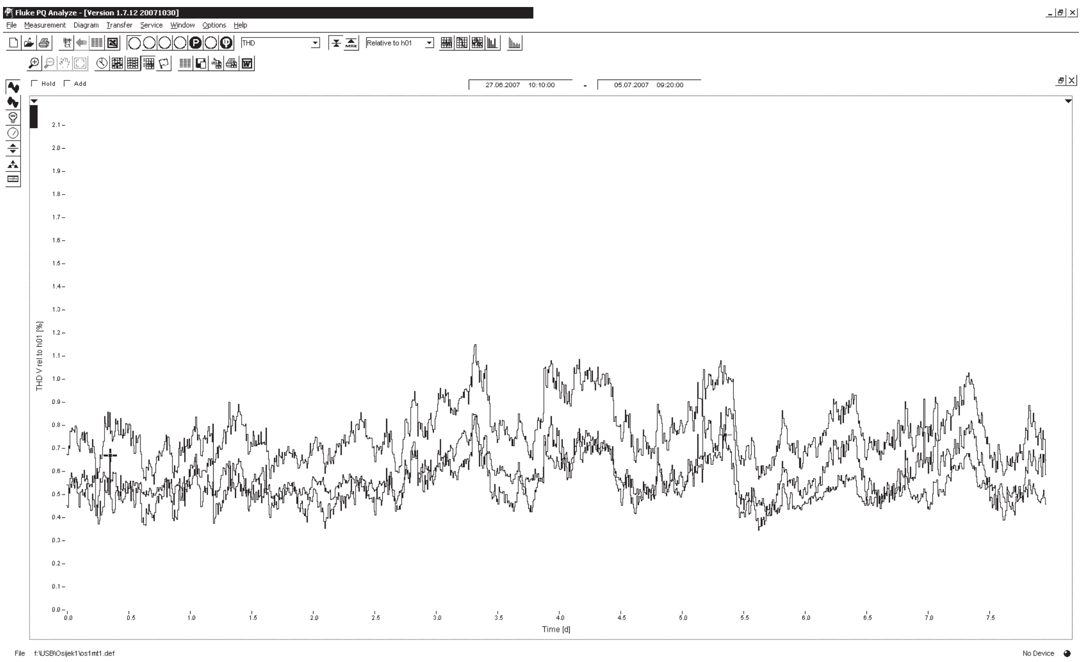

Figure 12 *Total voltage harmonic distortions THD_U at 110 kV level at MT1*
Slika 12. *Ukupno harmoničko izobličenje napona THD_U na 110 kV razini (MT1)*

4 Sample case
Primjer mjerenja

The real 110 kV distribution feeder at transformer substation TS 110/35 kV is considered for simultaneous power quality measurements at all voltage levels. Measurement terminal (MT) points are: 110 kV (MT1) and 35 kV (MT2) at TS 110/35 kV, 35 kV (MT3) and 10 kV (MT4) at TS 35/10 kV, 10 kV (MT5) and 0,4 kV (MT6) at TS 10(20)/0,4 kV, in the middle (MT7) and at the end (MT8) of the power line 0,4 kV with maximum load and in the middle (MT9) and at the end (MT10) of the longest power line 0,4 kV. The latest state-of the art three phase power quality analysers were used according to the European norm EN 50160. Power quality analysers used here are instruments in the class A (110 kV level) and in the class B (other voltage levels).

Power quality indices (including power harmonics aspect) of 110 kV (MT1) level are in compliance with EN 50160, unlike power quality indices at 10 kV voltage level (MT4) that are not in compliance with the norm caused by flickers aspect (Figures 10 and 11). As expected, there are remarkably more voltage variations, events and flickers at 10 kV voltage level. Also there is asymmetry of harmonics at 110 kV due to the impact of two phase transformer substation 110/25 kV (railway). Based on the performed measurements, it is evident that quality parameters become worse at lower voltage levels.

Total voltage distortion THD_U indices of 110 kV, 10 kV and 0,4 kV are easy to compare in Figures 12, 13 and 14. The maximum voltage distortion at 110 kV voltage level is around 1,1 % of the basic harmonic (50 Hz), the same index at 10 kV voltage level is around 2,3 % and at 0.4 kV voltage level is around 3,7 % of the basic harmonic. Voltage harmonic spectrum measured at 10 kV voltage level (MT4) with contributions of all harmonics in waveform is presented in Figure 15.

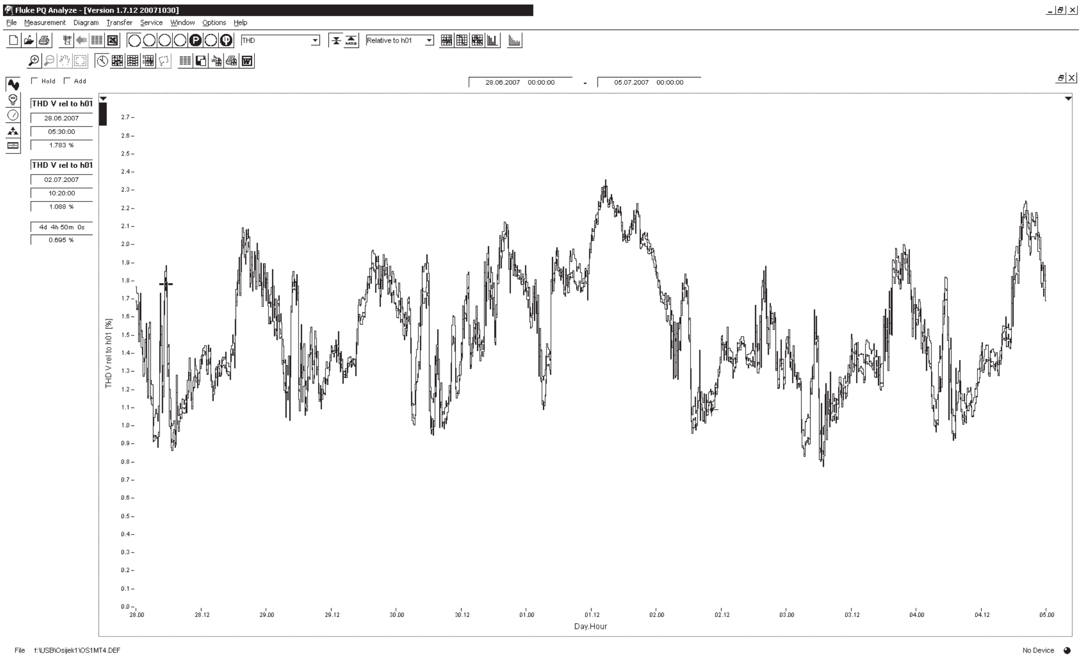

Figure 13 *Total voltage harmonic distortions THD_U at 10 kV level at MT4*
Slika 13. *Ukupno harmoničko izobličenje napona THD_U na 10 kV razini (MT4)*

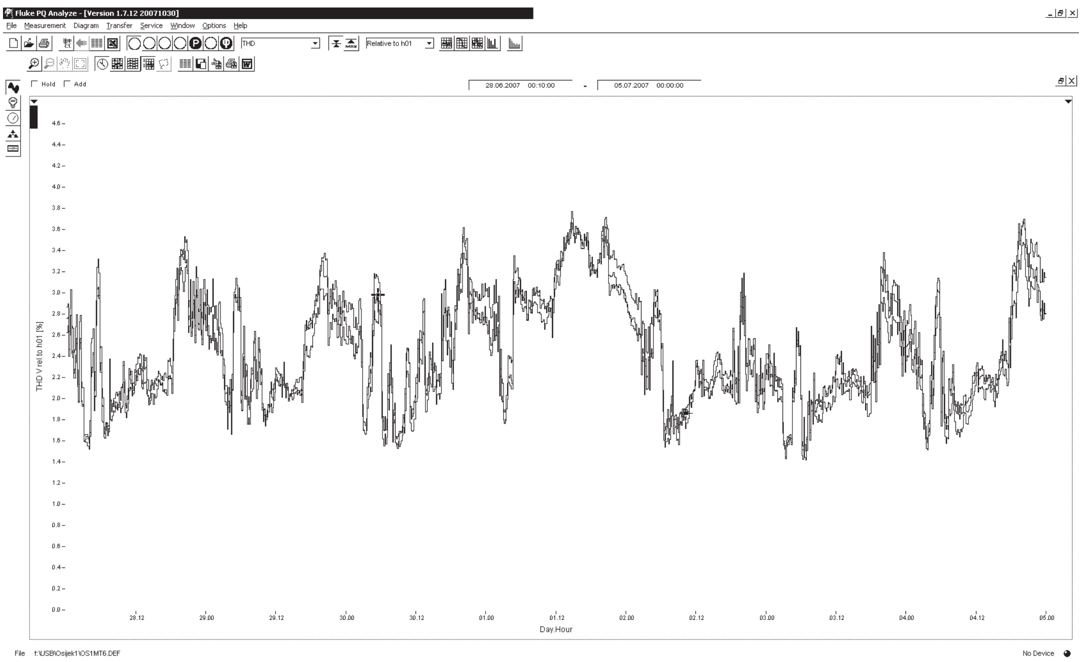

Figure 14 *Total voltage harmonic distortions THD_U at 0,4 kV level at MT6*
Slika 14. *Ukupno harmoničko izobličenje napona THD_U na 0,4 kV razini (MT6)*

5 Conclusion
Zaključak

Each power system's end-user and belonging non-linear load impacts total harmonics distortion level of supplied voltage. Partial consumer voltage harmonics distortion can be determined in connection points by proposed measurement and calculation methods. These methods' execution do not need existent consumers' disconnection to supply network. A brand new flow-chart is developed to recognise the consumer's THD generation amount. Further results of systematic planned measures that need to be done along the distribution power network will enable the determining of global THD level in distribution power system, finding out all the possible causes of harmonic distortion and simultaneously giving exact solutions. Here, an example of systematic power quality measurement at all voltage levels of the distribution network has been performed.

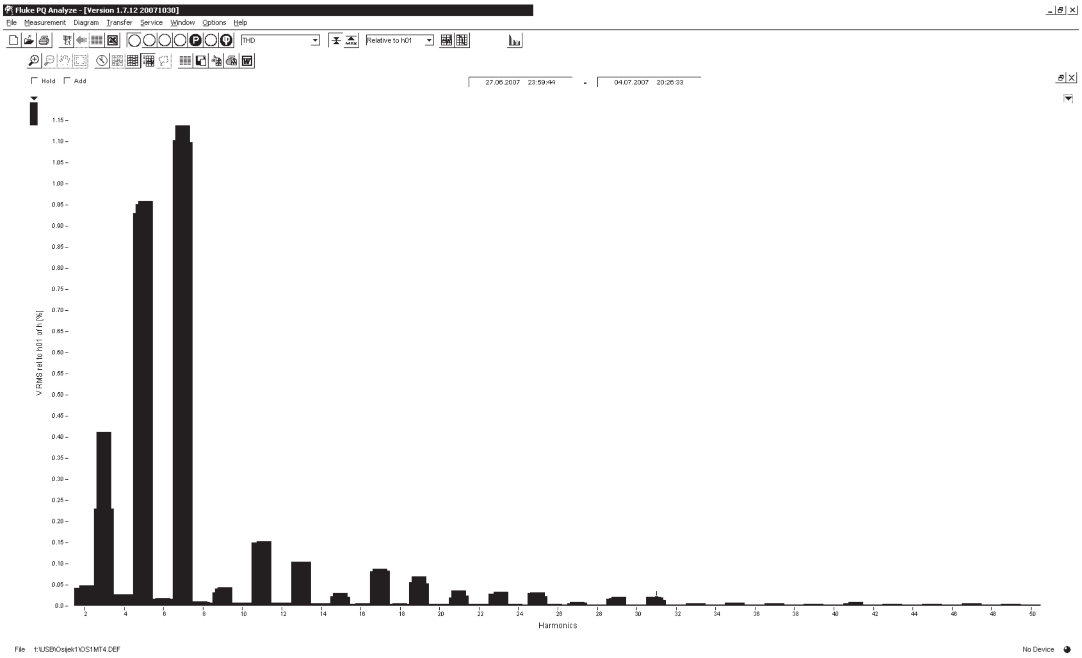

Figure 15 *Harmonic spectrum of 10 kV voltage level at MT4*
Slika 15. *Prikaz svih viših harmonika napona na 10 kV naponskoj razini (MT4)*

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