Erasmus+

e-Lab Prof Eng

Innovative Lifelong e-Learning for Professional Engineers (e-ProfEng)

Impact of PV Power Plants on Power Quality in Distribution Network

Zvonimir Klaić, Associate Professor

Faculty of Electrical Engineering, Computer Science and Information Technology Osijek

Josip Juraj Strossmayer University of Osijek

FERIT

INTRODUCTION

- The number of installed REPP, as well as other distributed sources, is increasing every day.
- From 2006 to 2016 (10-year period) total installed capacity of renewable power increased 3.41 times (“Renewables 2017 Global Status Report”)
- Conditions for cost-effectiveness of investments in the RES in the Republic of Croatia since 2007 (incentives)

These power plants are connected to the distribution grid:

- the passive distribution network becomes active
- the power plants also affect the power supply conditions in the power grid, on the power quality - **how do they affect it??**

Each of the RES, with regard to the type and technology, contributes to the power quality in the power system.

The impact of a particular power plant depends on:

- technology or type
- the parameters of the power grid at the connection site.

Future power plant's impact on the power grid can be predicted by simulations - the final status confirmation is measurements.

INFLUENCE OF REPP ON POWER QUALITY OF DISTRIBUTION NETWORK

Power conversion technology has a certain role in the power quality (wind and sun)

The power quality is mostly dependent on the interface and connection of the distributed generation and the type of connection with the electric power system.

Main types of interface and system connections are synchronous machines, asynchronous (induction) machines and electronic converters.

What is the power quality (quality of electricity)?

Roger Dugan, Mark McGranaghan, and Wayne Beaty in Electrical Power Systems Quality:

„**Power quality** is any power problem manifested in voltage, current, or frequency deviations that results in failure or missed operation of utility or end user equipment.”

Economists and power marketers see power as a product and **power quality** as a measure of the quality of that product.

What is the power quality (quality of electricity)?

Electricity is delivered by the voltage obtained from single-phase or three-phase systems, and has the following main parameters:

- Magnitude
- Frequency
- Wave form and
- Symmetry

Analysis of Power Quality usually includes following **PQ indices**:

- Voltage fluctuation
- Voltage dips and short interruptions
- Flickers
- Harmonics and interharmonics
- Overvoltage
- Transients
- Waveform distortion
- Voltage imbalance
- Power frequency variations
- Signaling voltages
- DC component

Power Quality indices

- are an effective tool for quantifying quality disturbances
- They also serve to evaluate compliance with **applicable standards** or recommendations.

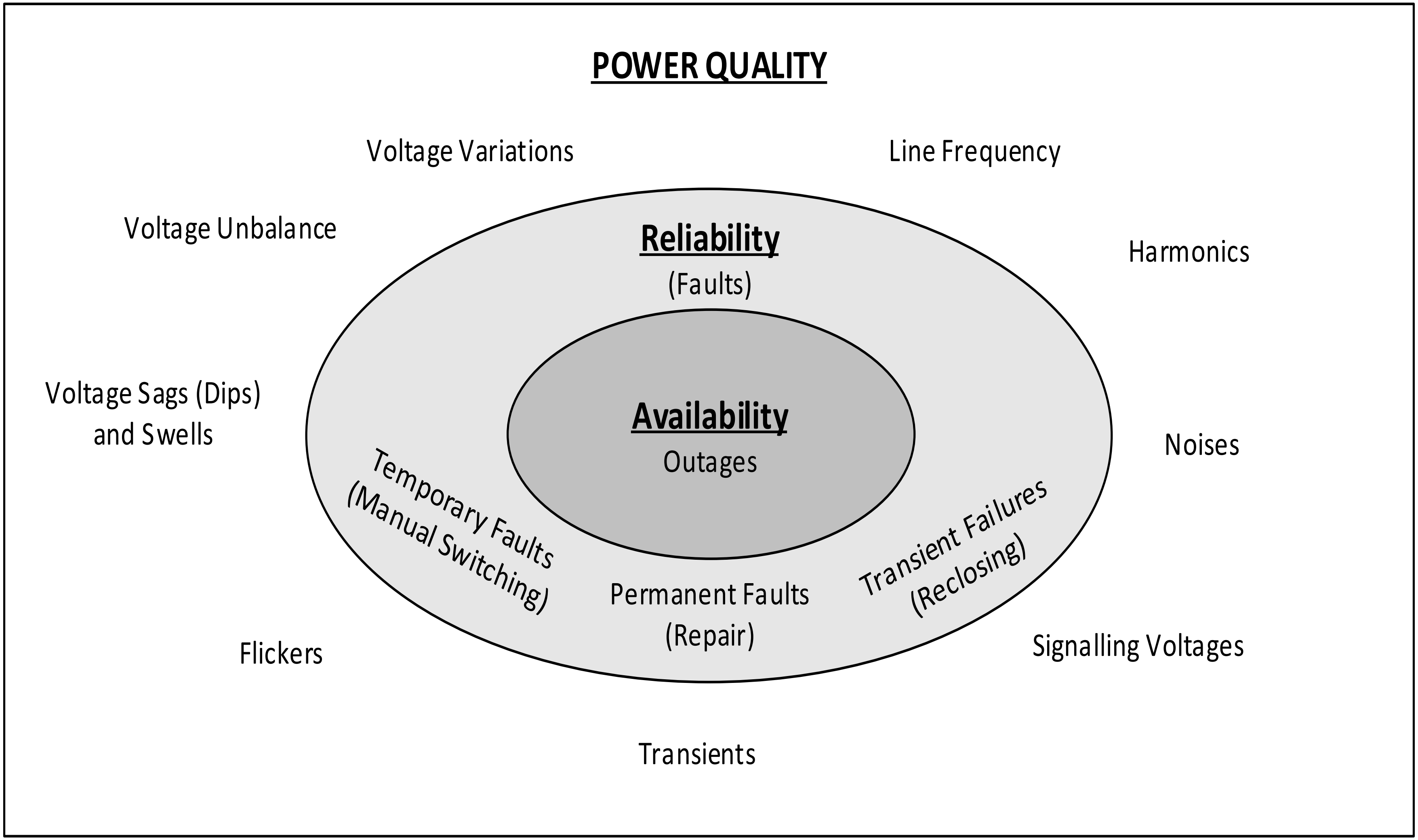
- European Union (EU) and Republic of Croatia (RH): EN 50160 „Voltage characteristics of electricity supplied by public distribution networks“ (EN 50160:2010).

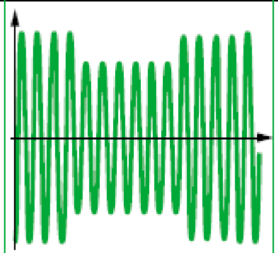
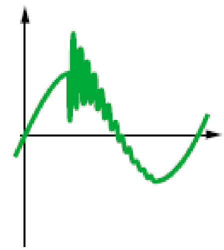
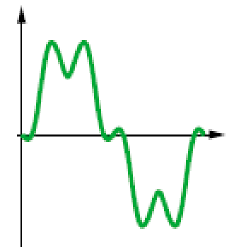
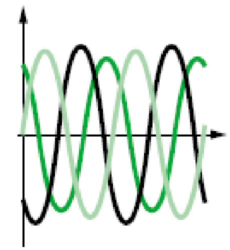
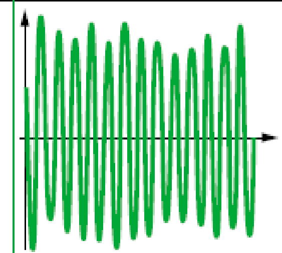
Standard EN 50160

- gives the main voltage parameters and their permissible deviation ranges at the customer's point of common coupling in public electricity distribution systems, under normal operating conditions.
- characterizes voltage parameters of electrical energy:
  - Magnitude
  - Frequency
  - Wave form and
  - Symmetry

EN 50160			
INDEX	MEAS. UNIT	Low voltage characteristics	Medium voltage characteristics
Voltage variations	V	±10 % U_n for 95 % of week	± 10 % U_c for 95 % of week
		+10/-15 % U_n for 5 % of week	
Short interruptions	Broj	< 3 min. – tens to hundreds per year	
Long interruptions	Broj	≥ 3 min. – < 10 – 50 per year	
Voltage dips	Broj	tens to thousand per year	
Voltage THD	% U_n	< 8 % U_n	
Flickers	P_{lt}	P_{lt} ≤ 1, za 95 % of week	
Asymmetry	% U_n	< 2 % U_n	
Frequency	Hz	± 1 % U_n for 99,5 % of year	
		+ 4/-6 % U_n for 100 % of time	

Power Quality Indices



Disturbances	Voltage dips	Overvoltages	Harmonics	Unbalance	Voltage fluctuations
Characteristic waveforms					
Origin of disturbance					
■ **Power system**					
□ Insulation fault, break of the neutral conductor...					
□ Switching, ferroresonance					
□ Lightning					
■ **Equipment**					
□ Asynchronous motor					
□ Synchronous motor					
□ Welding machine					
□ Arc furnace					
□ Converter					
□ Data processing loads					
□ Lighting					
□ Inverter					
□ Capacitor bank					

: Occasional phenomenon : Frequent phenomenon

Voltage Variations and Flickers

- The power network voltage is constantly changing due to the many switching of electrical equipment connected to the supply network.
- Voltage changes - slow: **variations** (increasing changes in total network load)

  - fast: **flickers** (intermittent changes in the high power loads)

The level of voltage changes that electrical equipment emits into the power supply network depends on the impedance of the network.

The higher the impedance, the higher the voltage variation level.

Voltage Variations

- A series of voltage changes or a periodic change of the voltage envelope
- The amplitude of these sudden changes generally does not exceed 6 - 8% of the rated voltage.

EN 50160:

- The voltage variation should not exceed ± 10 %.
- Situations like those arising from faults or voltage interruptions, the circumstances of which are beyond the reasonable control of the parties, are excluded.

Flickers or Voltage Fluctuations

- rapid changes in the voltage that arise as a result of the variable mode of large power machines operation
- short-term flickers (Pst) are measured and long-term (Plt) are calculated based on 12 consecutive Pst values:

$$P_{\mathrm{lt}} = \sqrt[3]{\sum_{i=1}^{12} \frac{P_{\mathrm{st}i}^3}{12}}$$

Limit in EN 50160: Plt = 1

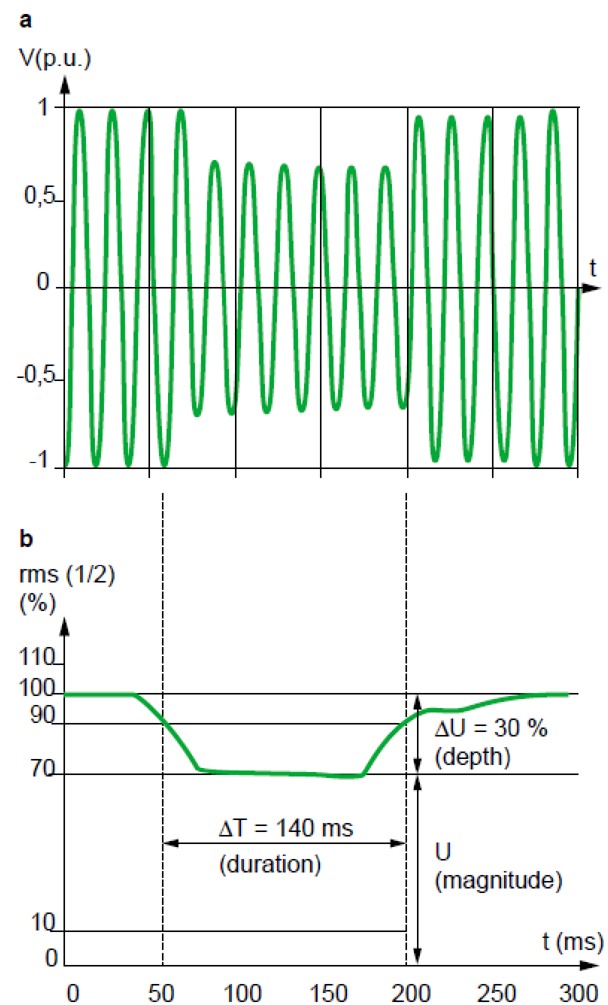
Grid Code: power plant contribution

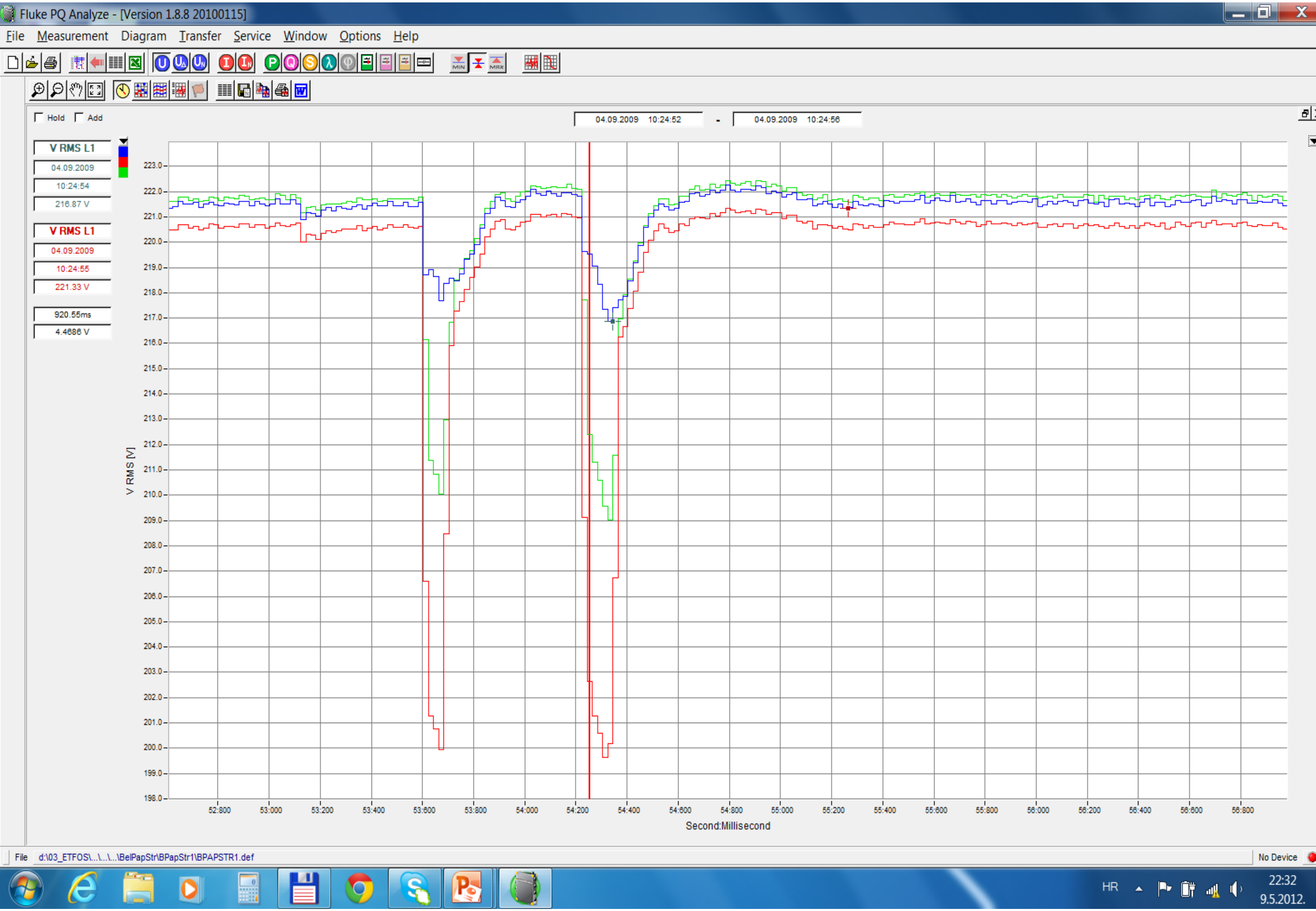
- short-term flicker: Pst = 0,7
- long-term flicker: Plt = 0,5

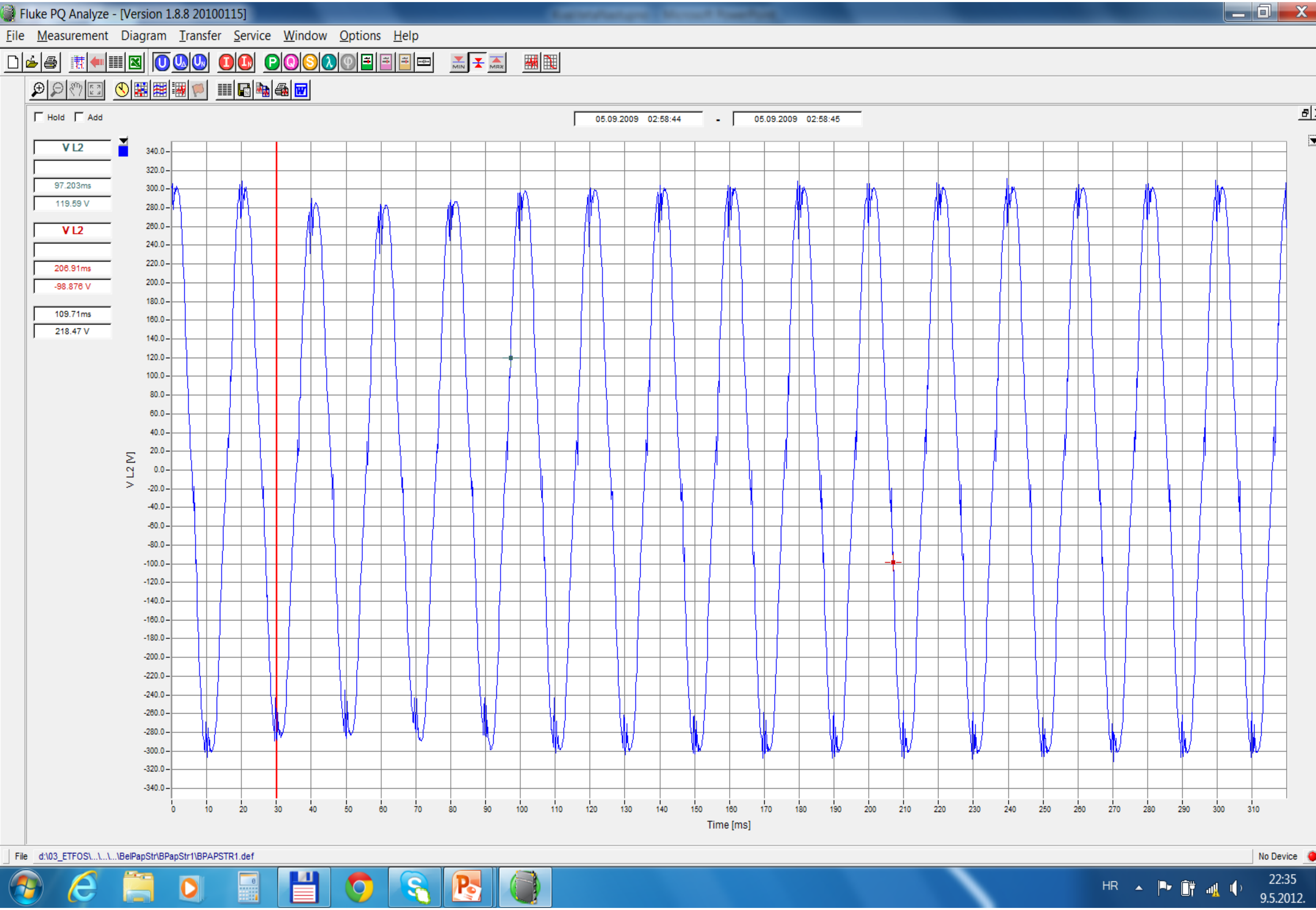
Voltage Dips and Interruptions

Voltage Dip

- two-dimensional electromagnetic disturbance, determined by the voltage level and duration
- sudden, short-term reduction in the effective value of the supply voltage
- they are mostly caused by short circuits and by starting the high power motors.
- Particularly sensitive equipment:
    - variable speed drives,
    - process control equipment,
    - computers




Fluke PQ Analyze - [Version 1.8.8 20100115]
File Measurement Diagram Transfer Service Window Options Help
Hold Add
04.09.2009 10:24:52
04.09.2009 10:24:56
V RMS L1
04.09.2009
10:24:54
216.87 V
V RMS L1
04.09.2009
10:24:55
221.33 V
920.55ms
4.4686 V
V RMS [V]
223.0
222.0
221.0
220.0
219.0
218.0
217.0
216.0
215.0
214.0
213.0
212.0
211.0
210.0
209.0
208.0
207.0
206.0
205.0
204.0
203.0
202.0
201.0
200.0
199.0
198.0
52:800 53:000 53:200 53:400 53:600 53:800 54:000 54:200 54:400 54:600 54:800 55:000 55:200 55:400 55:600 55:800 56:000 56:200 56:400 56:600 56:800
Second:Millisecond
File d:\03_ETFOS\...\...\...\BelPapStr\BPapStr1\BPAPSTR1.def
No Device
HR
22:32
9.5.2012.


Fluke PQ Analyze - [Version 1.8.8 20100115]
File Measurement Diagram Transfer Service Window Options Help
Hold Add
05.09.2009 02:58:44 - 05.09.2009 02:58:45
V L2
97.203ms
119.59 V
V L2
206.91ms
-98.876 V
109.71ms
218.47 V
V L2 [V]
Time [ms]
File d:\03_ETFOS\...\...\...\BelPapStr\BPapStr1\BPAPSTR1.def
No Device
HR
22:35
9.5.2012.

Voltage Dips and Interruptions

Voltage dips and interruptions extend to lower voltage levels (downstream) through a transformer

The number of affected phases and the depth of voltage dips depend on the type of fault and transformer connection.

On overhead networks exposed to bad weather, there are larger number of voltage dips and interruptions than in underground networks.

Voltage Dips and Interruptions

Phase L1, L2, L3	< 20 ms	20...< 100 ms	100...< 500 ms	0.5...< 1 s	1...< 3 s	3...< 20 s	20...< 60 s	>= 1 min
Surge > 10.00%								
Dip > 10.00%								
10...< 15 %								
15...< 30 %								
30...< 60 %								
60...< 99 %								
Interruption								

Recording as events from -10.00/+10.00% of the nominal voltage

Dip according to UNIPEDE measurement guide

Voltage dips and interruptions classification according to UNIPEDE - International Union of Producers and Distributors of Electric Energy.

Erasmus+

e-Lab Prof Eng

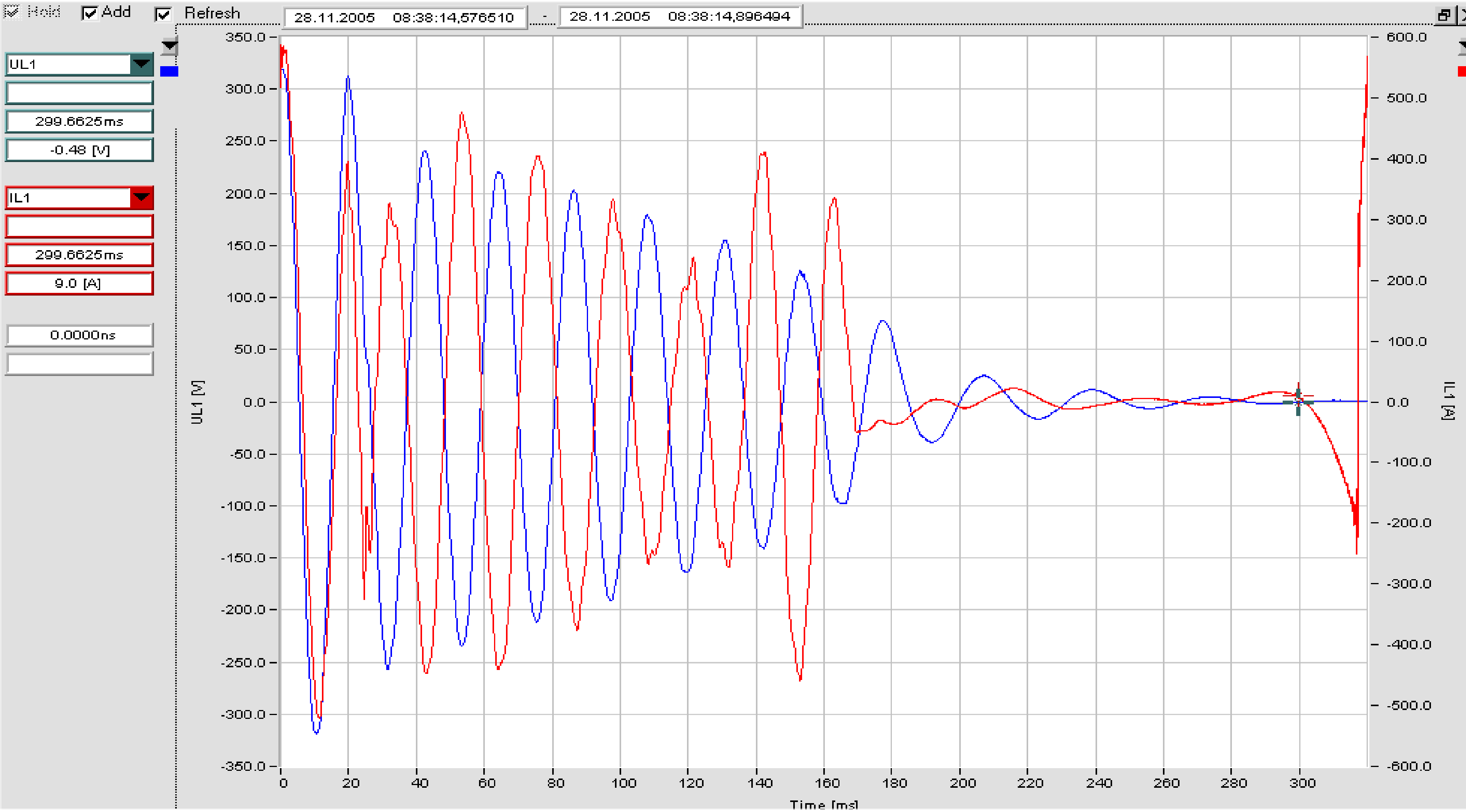
Voltage Dips and Interruptions

Voltage interruption:

- is defined as a condition in which the supply voltage at delivery site is less than 1% of rated (agreed) voltage.

There are long-term interruptions (> 3 minutes) and short-term interruptions (≤ 3 minutes), both planned and unplanned.

Long-term interruptions are the consequence of the isolation of a permanent fault with protective devices or the conscious opening of the switch due to partial failure.

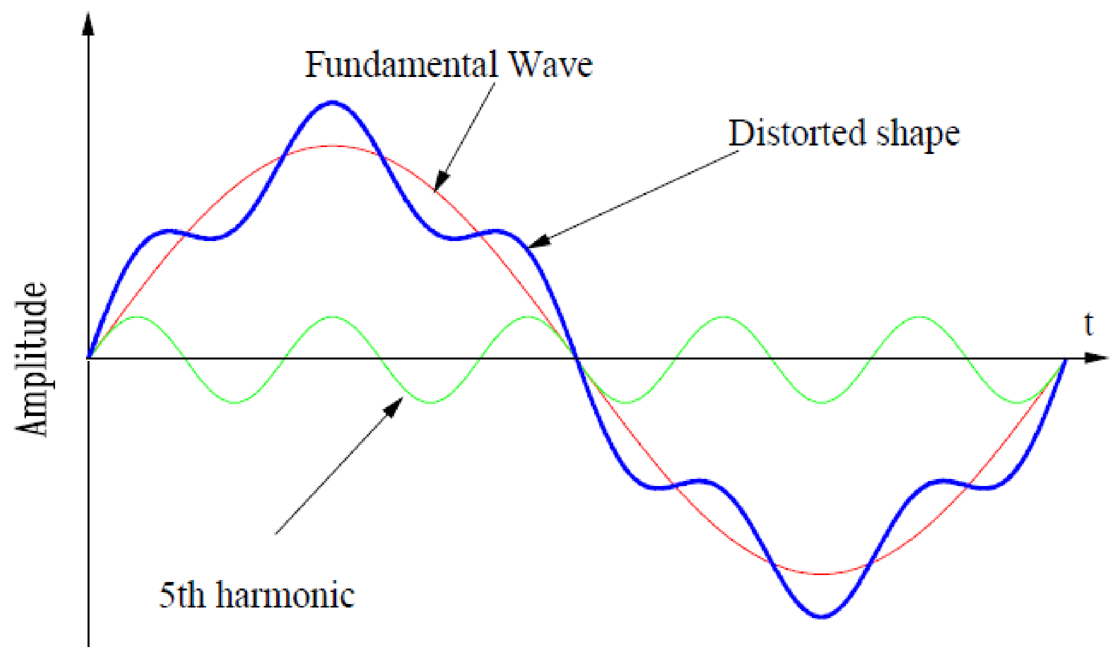


Waveform of short interruption

Voltage Harmonics

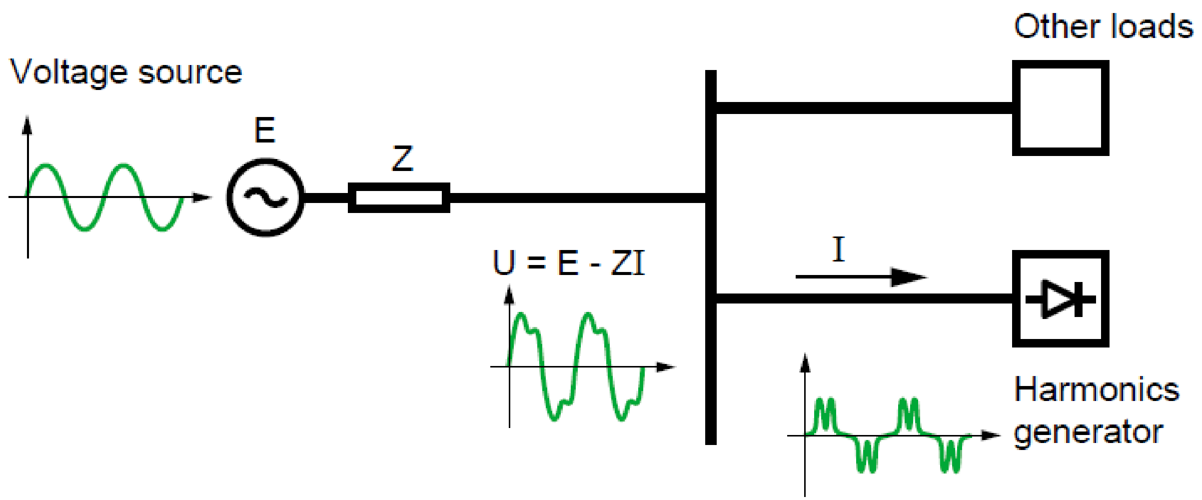
The harmonics are sinusoidal voltages or currents with frequencies that are multiples of the rated frequency - the frequency at which the power system operates (e.g. 50 Hz in Europe).

All periodic functions of the frequency f can be separated into the sum of the sinusoidal Waveforms of the frequency $h \times f$



Voltage Harmonics

Harmonic disturbance levels have been accelerating in recent years due to the widespread use of nonlinear semiconductor devices that cause most of the harmony disorder.



Distortion of the signal is calculated by the coefficient of total harmonic distortion THD:

$$THD\mathrm{U} = \sqrt{\sum_{h=2}^{40} \left(U_h\right)^2} \frac{100\%}{U_1}$$

THD gives the sum of the effective voltage values of all harmonic frequencies, and is displayed relatively to the base voltage harmonic.

Voltage Harmonics

The effects of Harmonic have an economic impact resulting from the additional costs linked to:

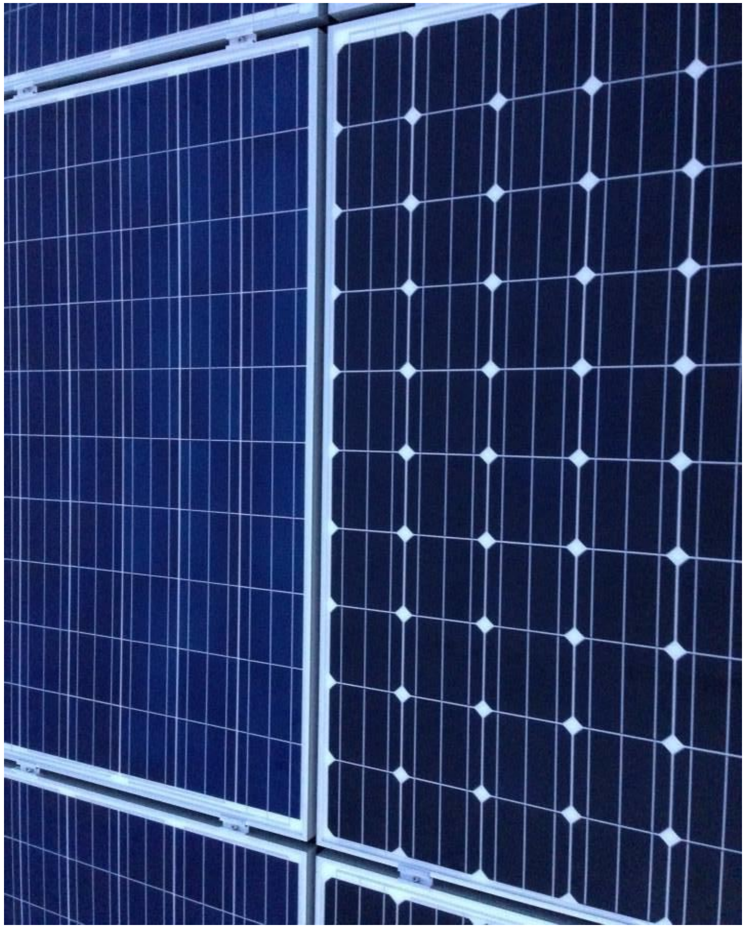
- Degradation in the energy efficiency of the installation (energy loss)
- Oversizing of equipment
- Loss of productivity (accelerated ageing of equipment unwanted tripping)

Voltage Harmonics

There are three possible ways of suppressing or at least reducing the influence of harmonics:

- Reducing generated harmonic currents
- Modifying the installation
- Filtering

The Impact of PV on Distribution System – Power Quality Measurements



Photovoltaic power plant – renewable-based DG:

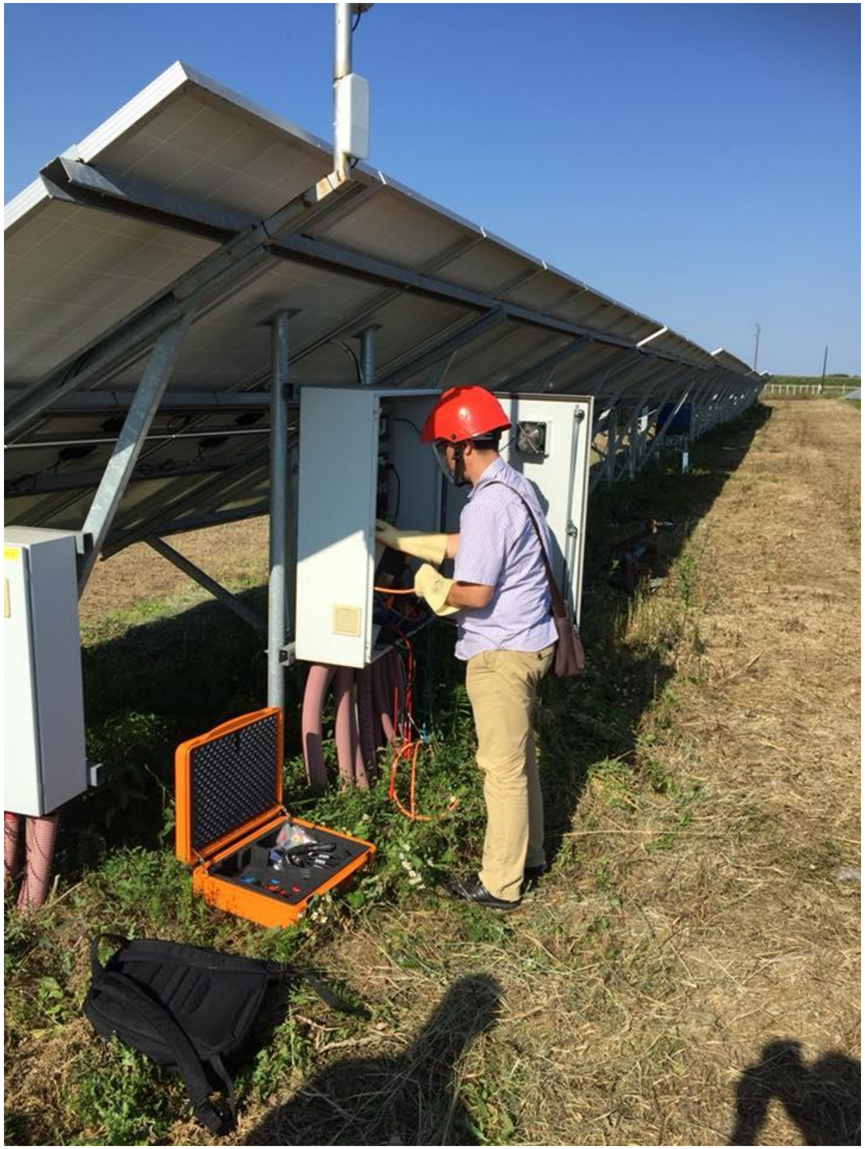
- generate **DC** power,
- have **inverters** as interface to the distribution system.

power inverters + variable power flow of the PV = **harmonics** in the output PV current.

In the photovoltaic power plant, the most important part, considering power quality is a inverter that inverts the direct current from photovoltaic modules into alternating current

The innverter has several functions:

- control the photovoltaic route
- adjusts the current and voltage to maximize the power output from the photovoltaic modules



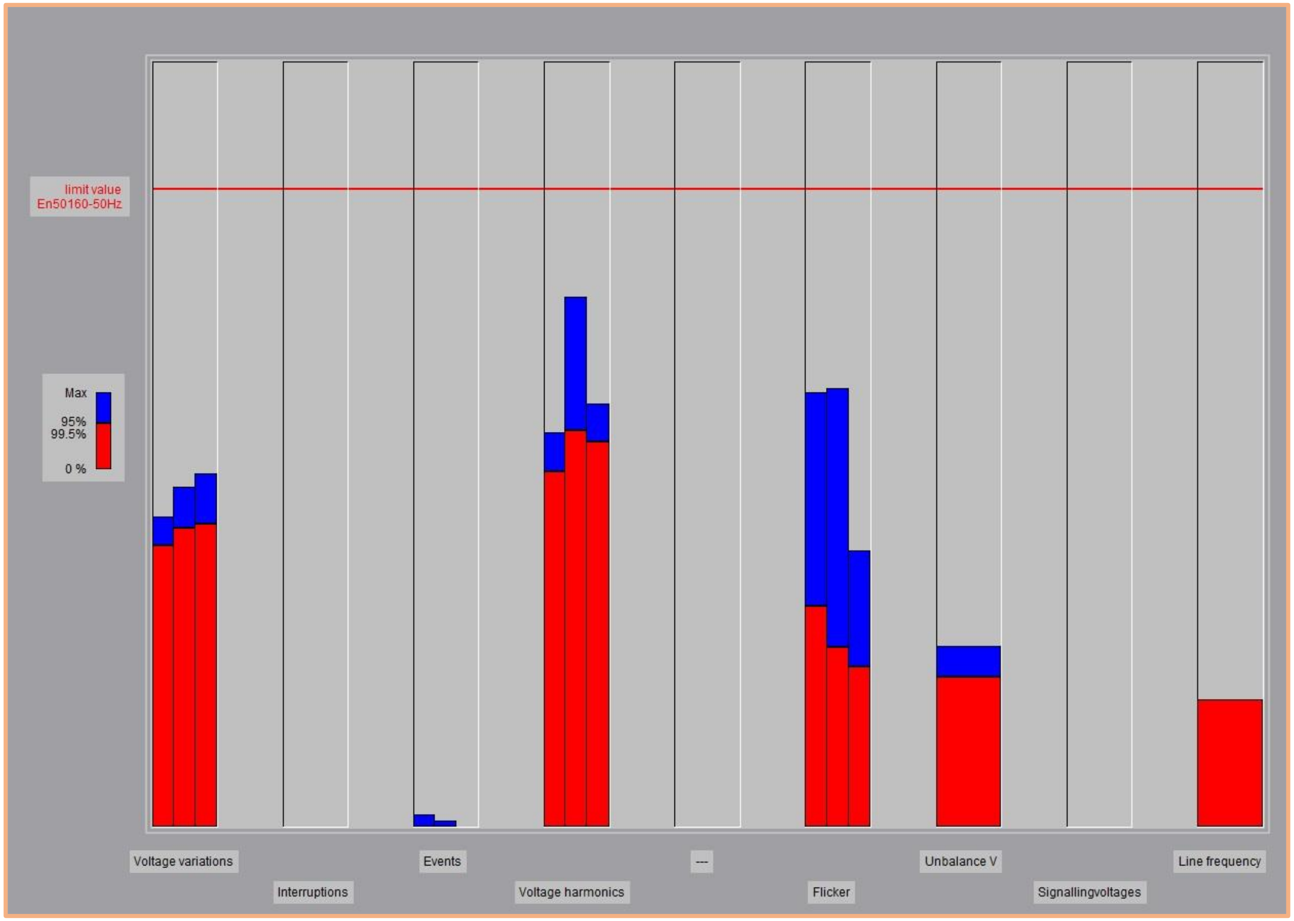
ANALYSIS OF POWER QUALITY MEASUREMENT RESULTS

Power quality measurements

- Before and after the connection of PV on the distribution grid
- According to EN 50160 – 7 days before and 7 days after the connection
- According to IEC 61000-4-30 – analyzer class A

The results of Power quality measurements:

- According to EN 50160
- According to Croatian Grid Code



August 2018. – NEW GRID CODE for distribution

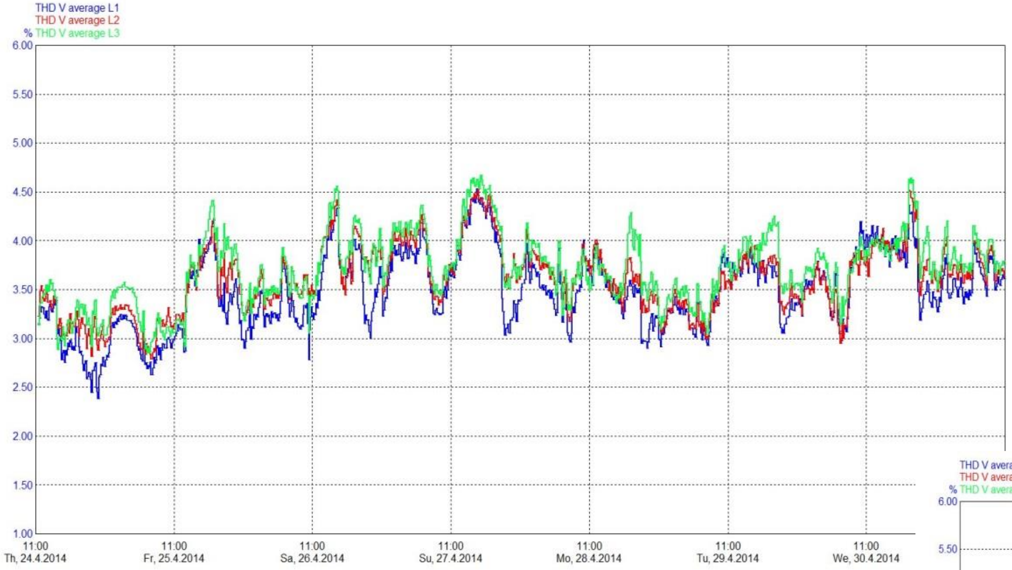
Analisys of Power quality measurements according to the **OLD** Croatian Grid Code:

- Limits for **Voltage** fluctuations and **Frequency** variations simmilar to EN 50160

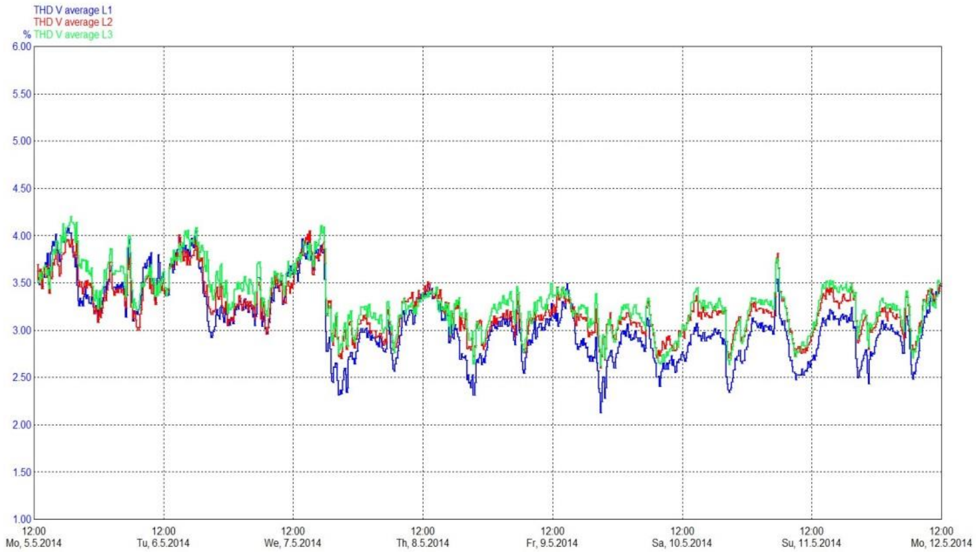
- Allowed contribution of power plant on distribution grid for

  - **THD_U**, (2,5 % U_n, for 0,4 kV level)
  - **Flikers** and
  - Voltage **imbalance.**

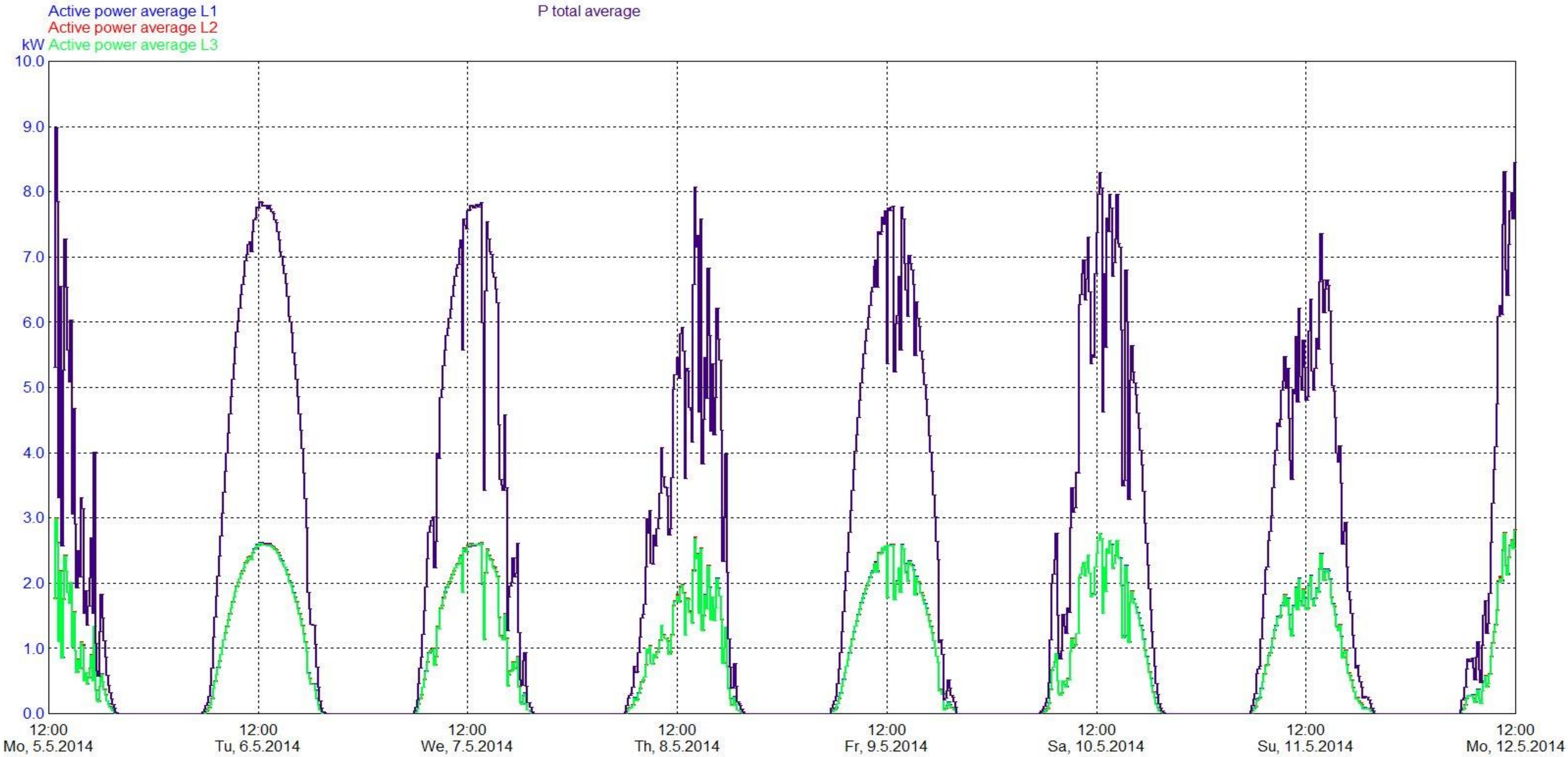
This is the reason for analysis of power quality measurements **before** and **after** the connection of PV on the distribution grid.



Total harmonic distortion, THD_U (% U_n), before the connection of PV.



THD_U (% U_n), after the connection of PV



The real power delivered to distribution grid from PV power plant – during 7 days test operation of PV.

Voltage deviation		
Range	Limit	Mark
230 V ± 10%	95,0 %	OK
230 V +10%/-15 %	100,0 %	OK
Frequency deviation		
Range	Limit	Mark
50 Hz ± 1%	99,5 %	OK
50 Hz +4%/-6%	100,0 %	OK
THD		
Range (contribution)	Limit	Mark
<2,5 %	95 %	OK
Imbalance		
Range (contribution)	Limit	Mark
<1,3 %	95 %	OK
Flickers		
Range (contribution)	Limit	Mark
Pst (shortterm) < 0,7	95,0%	OK
Plt (longterm) < 0,5	95,0 %	OK
Power factor		
Range	Limit	Mark
Definiran u EES	100%	OK
Influence on signal		Mark
		OK

Photovoltaic Power Plants

RESULTS OF POWER QUALITY MEASUREMENTS – **PHOTOVOLTAIC** POWER PLANTS

From 2011 - 7 years

An analysis of the power quality measurements during integration of 7 PVPPs in the electricity distribution grid in Eastern Croatia.

	PV POWER PLANTS						
Facility name	Nom. Power [kW]	Voltage variation	Events	Voltage harmonics	Flicker	Unbalance	Line frequency
PV1	30				-		
PV2	10	+	+	+	+		
PV3	200				-		
PV4	10		+		+		
PV5	30	-					
PV6	30				+		
PV7	300				-		

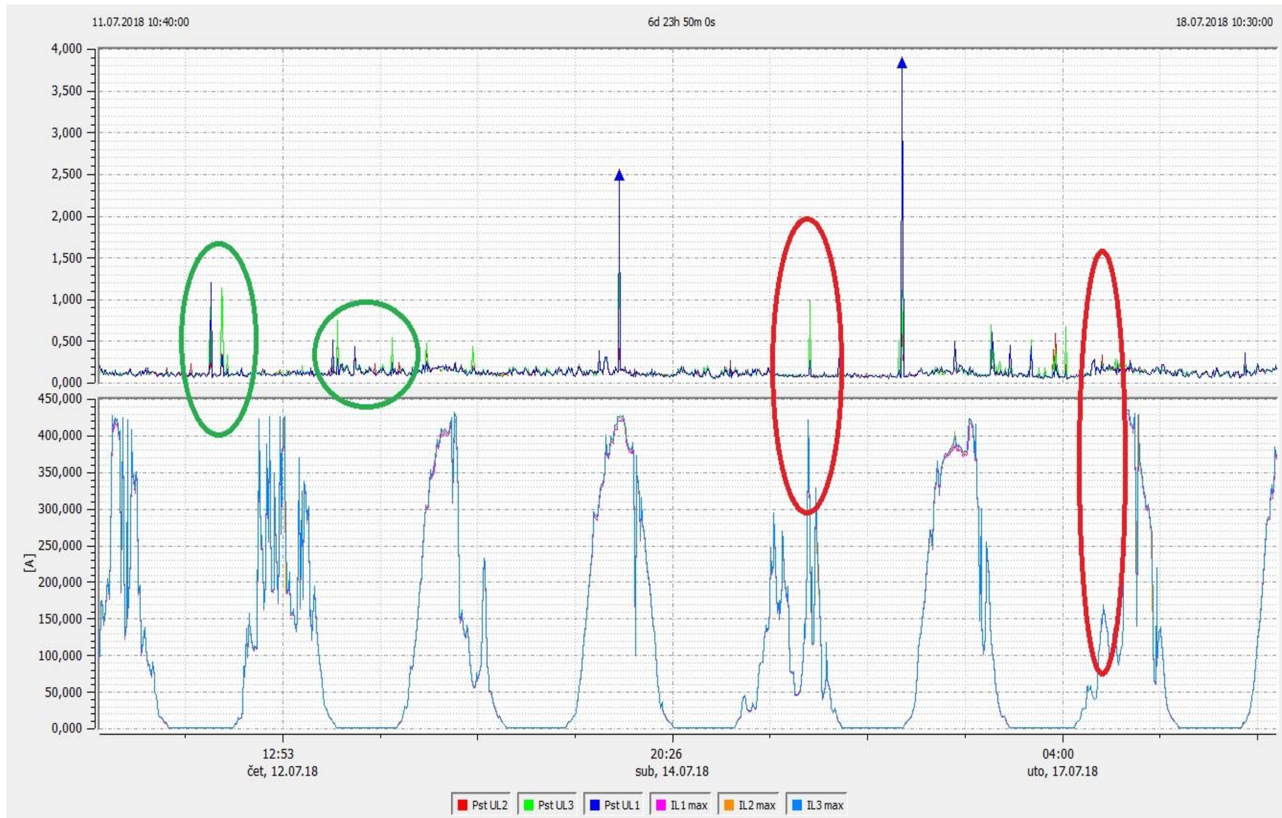
Measurement results:
All PQ indices in all PVPPs were in compliance with the requirements of EN 50160 and the Croatian Grid Code.

300 kW photovoltaic power plant PV7

Most flickers $P_{st} < 0.2$

Some peak values were caused by changes in PV production.

Most of them were happened when PV was inactive.



P_{st} (upper diagram) and I_{max} (lower diagram) – PV7

Erasmus+

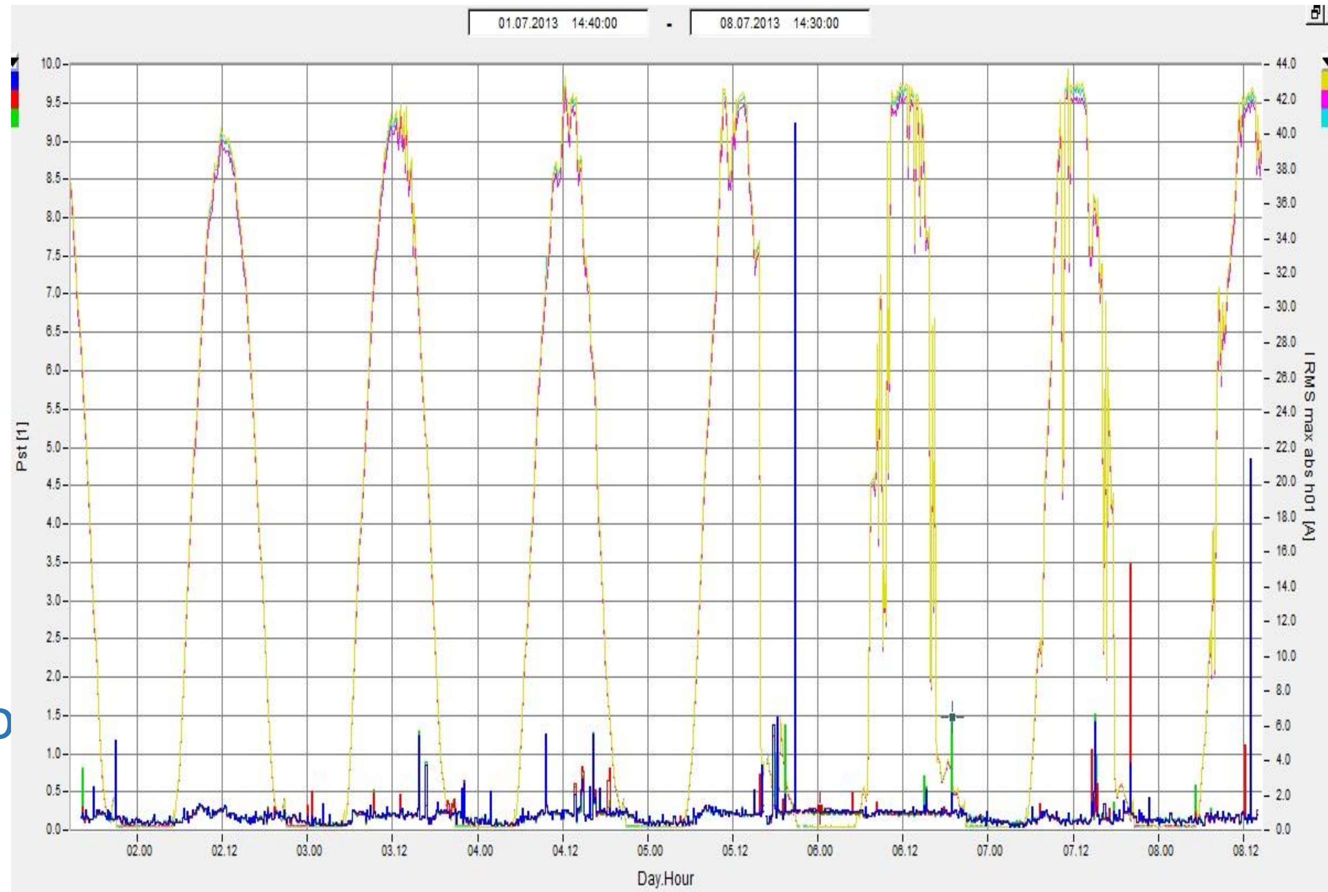
e-Lab Prof Eng

30 kW photovoltaic power plant PV1

Most flickers $P_{st} < 0.3$

Most flickers were caused by fast changes in PV production.

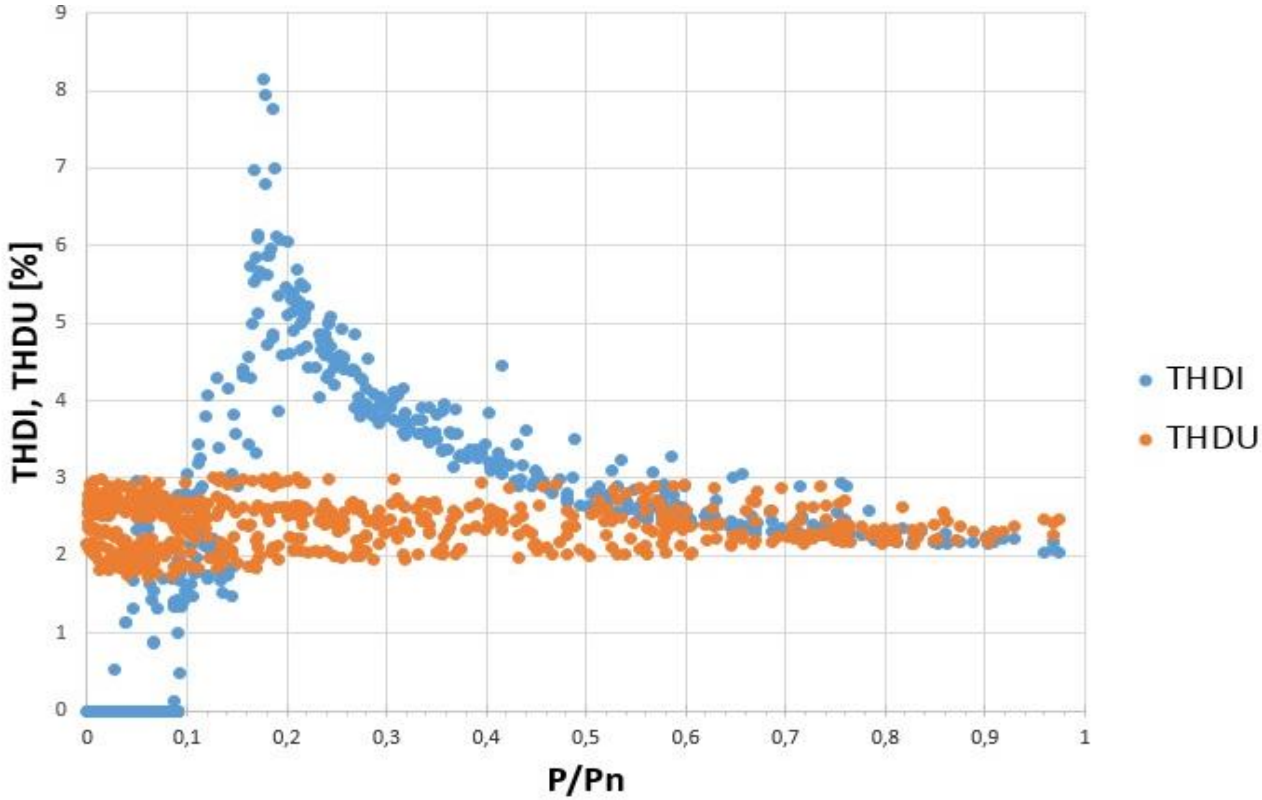
Nevertheless, all measured values were in accordance to EN 50160 and Croatian Grid Code.



P_{st} and I_{max} – PV1

There was no significant harmonic worsening in any PV power plant measurement. An analysis - changes in sunlight have no significant effect on the voltage harmonics recorded at the connection point of the particular photovoltaic power plant.

The recorded data – there is no correlation between the voltage harmonics and the production of the photovoltaic power plant.



THDI and THDU in different production conditions of PV5

Renewable Energy Journal 2012:
Expansion of the Residential Photovoltaic Systems and its Harmonic Impact on the Distribution Grid

Kresimir Fekete, Zvonimir Klaic and Ljubomir Majdandzic

The presence of a large number of grid-connected PV systems

Possible power quality problems:

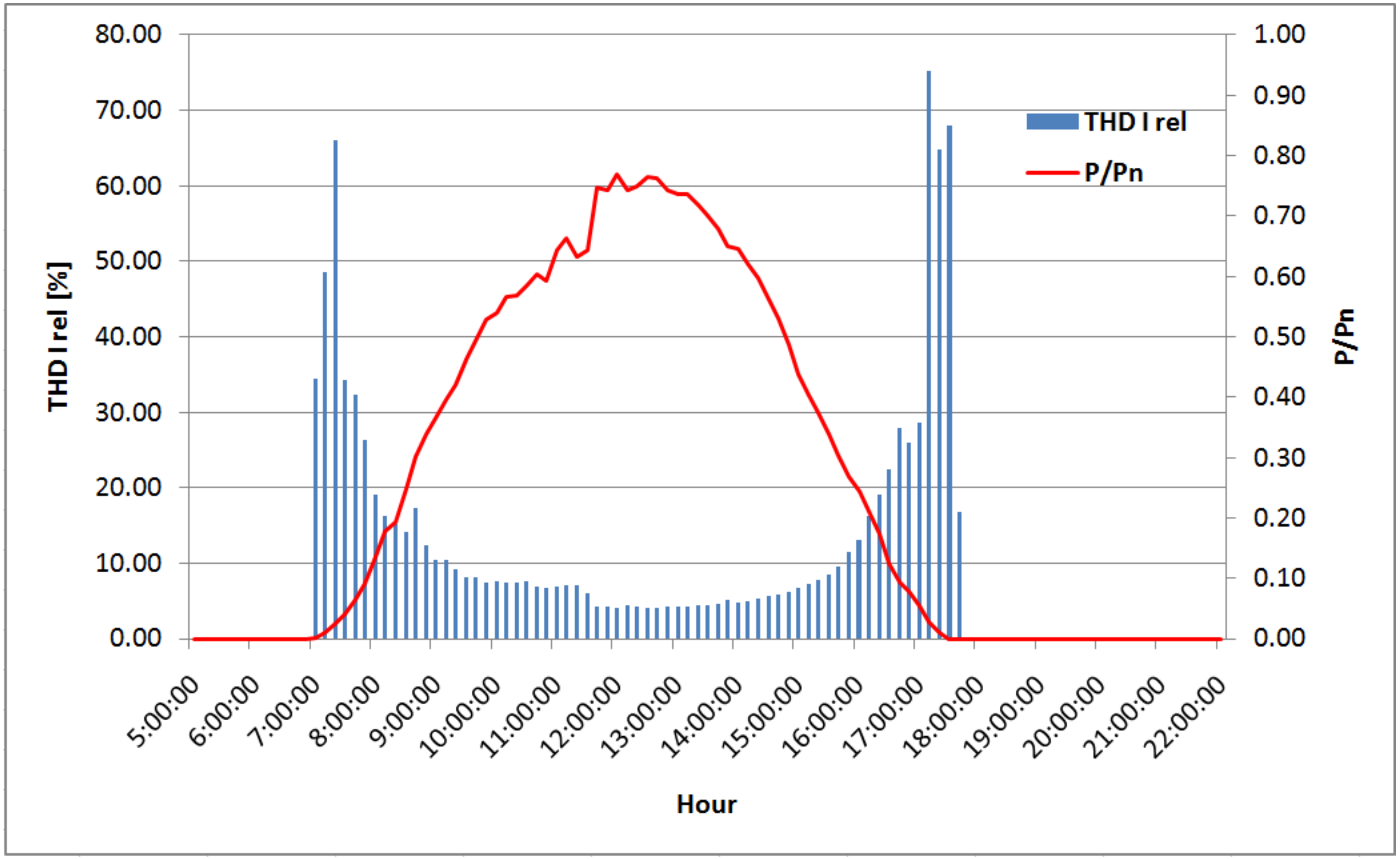
- **harmonics** are presented in the output PV current - the use of power converters
- variable power flow of the PV system due to weather conditions – **voltage fluctuation, flicker**

These currents, flowing through the impedances of the distribution system (variable with frequency), results in a distortion of system voltage

The size of most residential PV systems is very small compared to short-circuit power of the distribution grid - as far as system voltage distortion is concerned, the effect of the single PV plant operation is almost negligible.

But, the number of the PV systems connected to the same local grid is increasing and the question is will that affect on the grid voltage harmonics?

Harmonic currents are produced by PV system. How they affect on power quality?



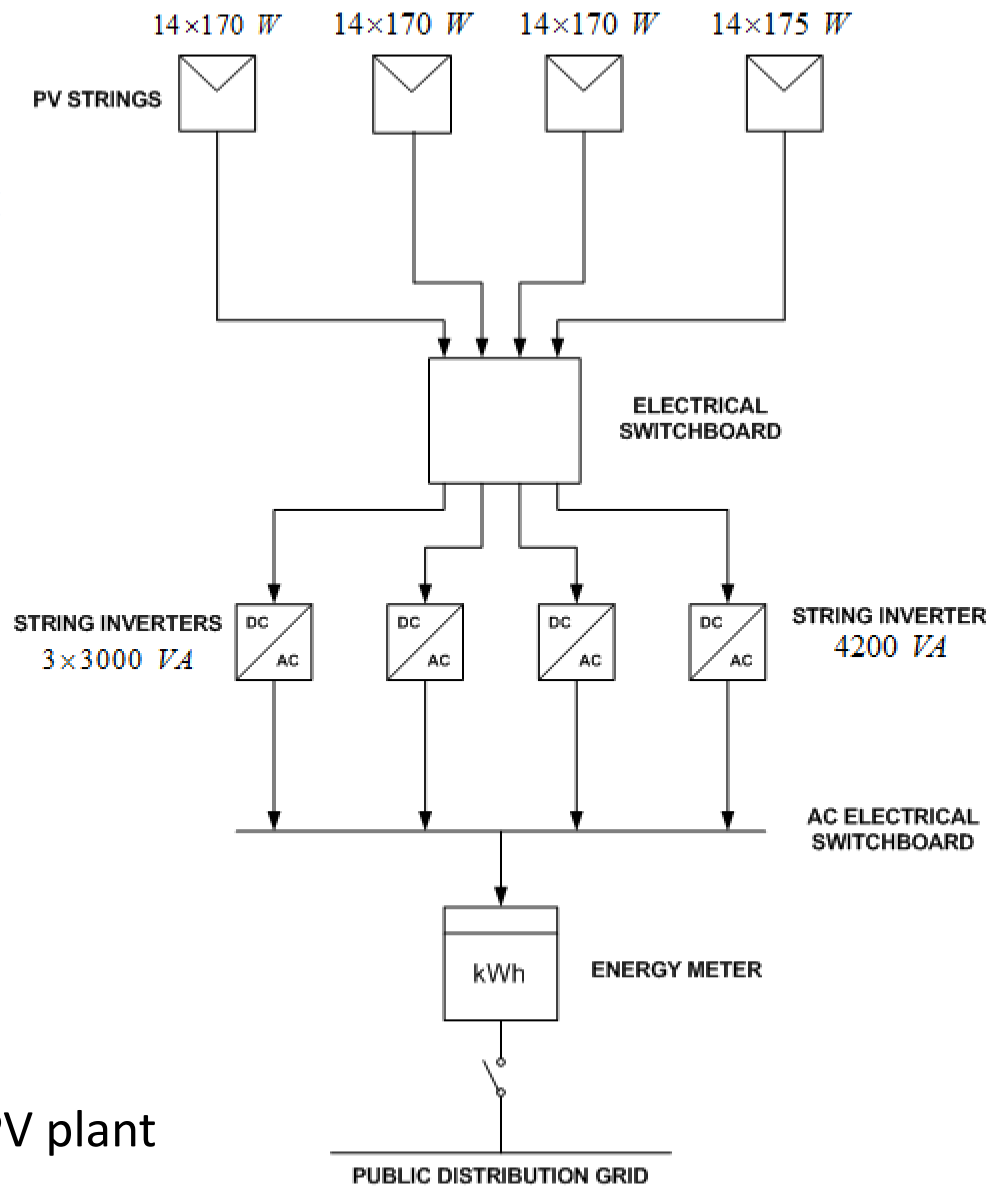
Daily evolution of the generated power and THD_I for average winter day

Istraživanje:

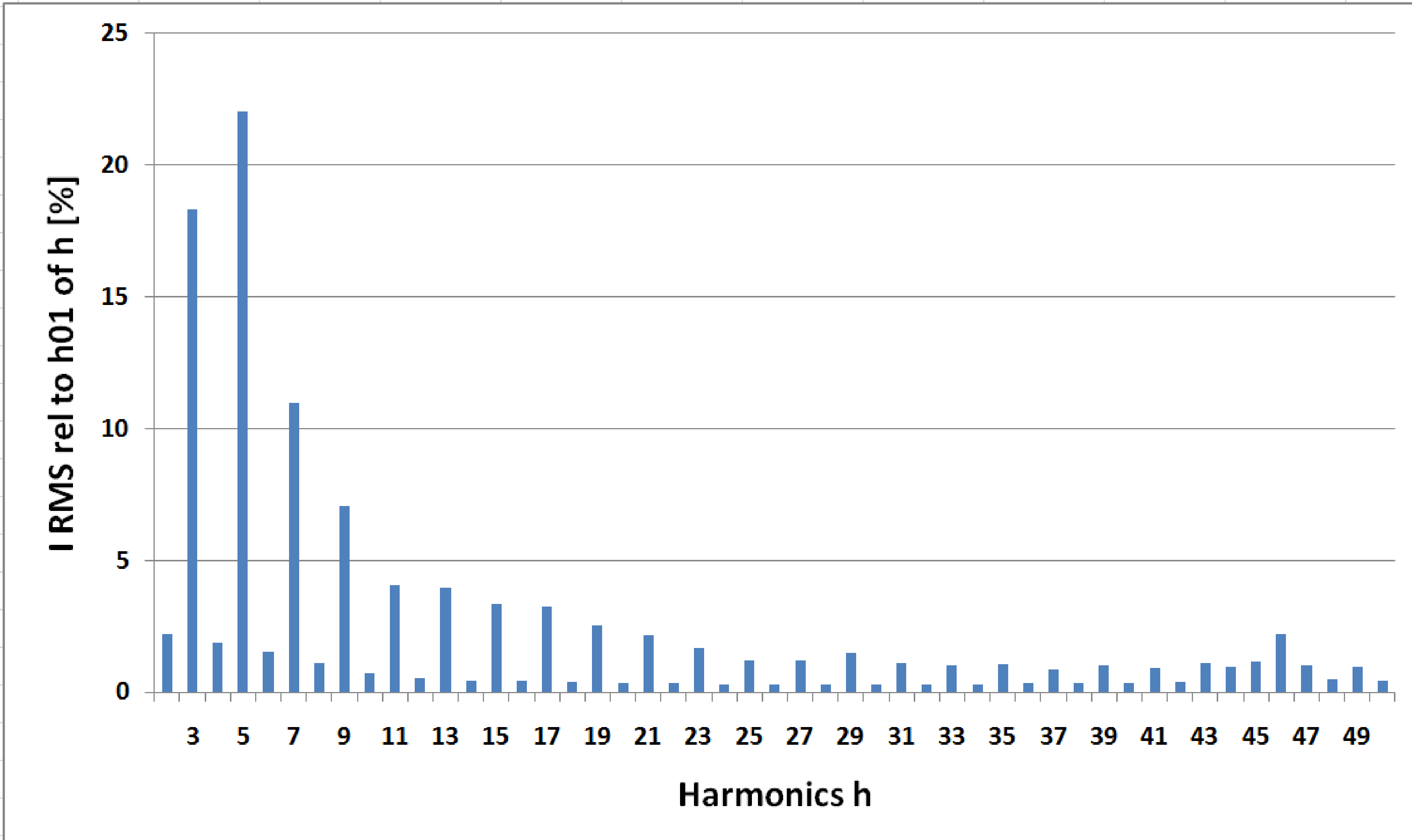
1. Power quality measurements:

10 kW PV in two 7-days periods:

winter and summer



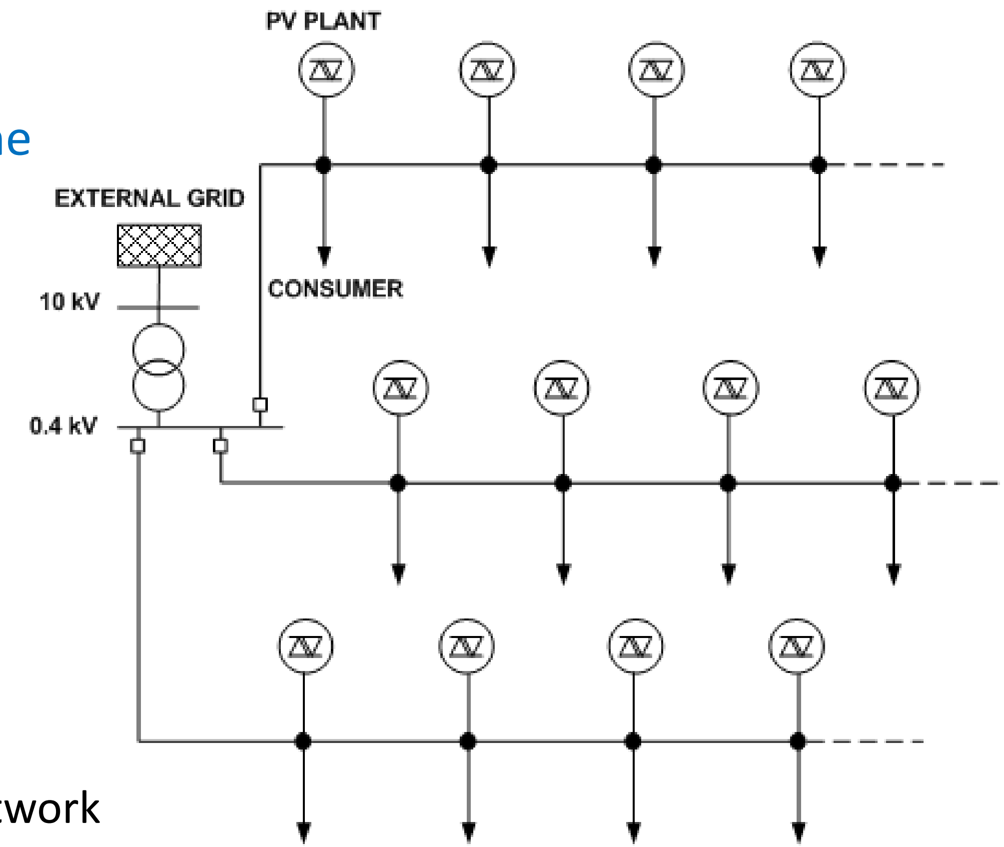
Layout of the 10 kW residential PV plant



Harmonic spectrum of the PV current signal

Research:

1. DigSILENT Power Factory software package is used to create a computer model of PV plant and local distribution network.
2. Four cases are analyzed using simulation model in order to find the case that has the most negative impact on the system voltage.



Part of the modeled distribution network

1. **First scenario** of the PV plant penetration

On the every third bus (house) in the model, PV plant with same characteristic is connected. After the harmonic load flow is done, THD_U of 1% is obtained at the PCC.

2. **Second scenario** of the PV plant penetration

On the every bus (house) in the model, PV plant with same characteristic is connected. As a result of the simulation THD_U of 2.71% is obtained at the PCC.

3. **Third scenario** of the PV plant penetration

This scenario attempts to capture mutual influence of PV harmonic impact and already present harmonic sources in the distribution network.

First variant is combination with scenario 1 when one third of the households installed PV plant

Second variant is combination with scenario 2 when all the households installed PV plant.

Rezultati:

First variant - THD_U on PCC is 2.46 %

Second variant - THD_U on PCC is 3.66 %.

Erasmus+

e-Lab Prof Eng

Conclusion

	Scenario/Variant			
	Sc. 1	Sc. 2	Sc. 3/Var. 1	Sc. 3/Var. 2
THD_U at PCC (%)	1.00	2.71	2.46	3.66

The simulation results indicate that highest harmonic distortion of system voltage due to PV plants operation is when all the households install PV plants.
This case presents extreme scenario of residential PV plant expansion.
However, such a development is unlikely in the near future.

All THD_U values for all simulation scenarios are below treshold from EN 50160, $THD_U < 8$ %

Energies Journal 2019:

Harmonic Distortion Prediction Model of a Grid-Tie Photovoltaic Inverter Using an Artificial Neural Network

Matej Žnidarec, Zvonimir Klaić, Damir Šljivac and Boris Dumnić

Expanding the number of photovoltaic (PV) systems integrated into a grid raises many concerns regarding protection, system safety, and power quality.

This paper presents long-term **current harmonic** distortion prediction models:

- multilayer perceptron neural network, (a type of artificial neural network (ANN)), with
- input parameters that are easy to measure in order to predict current harmonics.

The models were trained with one-year worth of measurements of

- power quality at the point of common coupling of the PV system with the distribution network
- and the meteorological parameters measured at the test site.

A total of **six different models** were developed, tested, and validated regarding a number of hidden layers and input parameters.

Erasmus+

e-Lab Prof Eng

Description of the Site

A **10-kWp PV plant** is an outdoor component of the Laboratory for Renewable Energy Sources at the Faculty of Electrical Engineering, Computer Science, and Information Technology (FERIT) Osijek.

The PV plant is installed on the roof of the FERIT Osijek building with a 7 deg. tilt angle.
It consists of 2 5-kWp PV arrays connected to a three-phase grid-tie inverter, which is connected to a 230 V AC, 50 Hz distribution network via the building's electrical switchboard.

Each array consists of 20 series-connected 250 Wp PV modules.
The first array consists of monocrystalline silicon, while the second consists of polycrystalline silicon PV modules.

Table 1. Technical characteristics of the photovoltaic (PV) plant inverter [17].

Manufacturer	**Kaco**
Model	Powador 12.0 TL3
Circuit design	6-pulse transformerless IGBT [1]
DC side	
Parameter	Value
Maximum PV generator input power (kW)	12
Maximum power point voltage range (V)	280–800
Starting voltage (V)	250
Maximum open-circuit voltage (V)	1000
Number of string inputs	2
Maximum short-circuit current (A)	22.4
AC side	
Rated power (kW)	10
Rated current (A)	14.5
Grid voltage (V)	400/230
Distortion factor (THDI) (%)	2.22
Maximum efficiency (%)	98
European efficiency (%)	97.5

[1] IGBT: insulated gate bipolar transistor.

Measurement Procedure

The measurements used for our analysis were obtained by the **data acquisition system** developed by the Laboratory for Renewable Energy Sources of the FERIT Osijek.

The data acquisition system simultaneously and continuously **measures, analyzes, and stores** electrical and meteorological data at the test site in local and cloud databases.

- measurements of solar irradiance, ambient temperature and power quality measurements

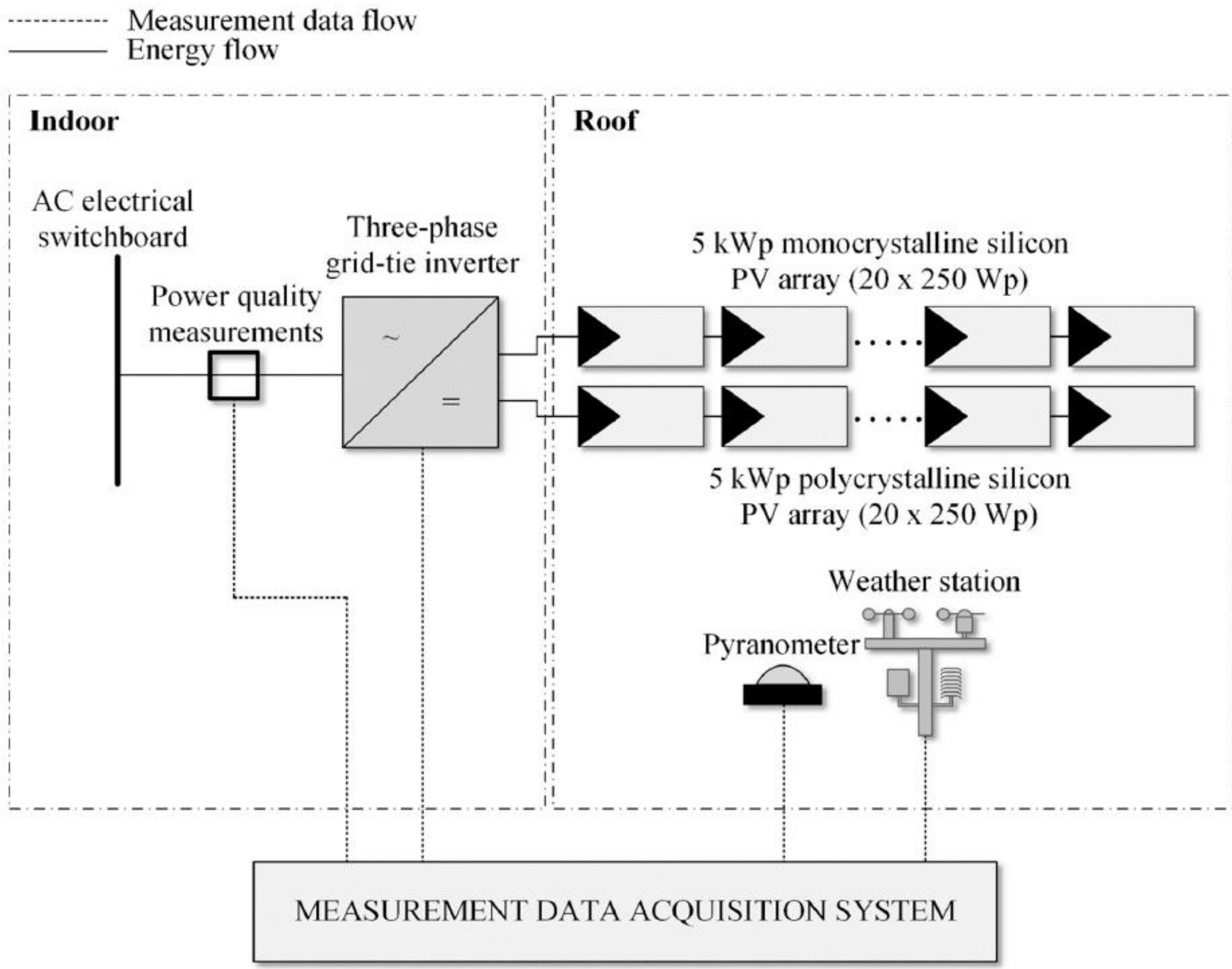


Figure 1. Scheme of the 10-kWp PV plant and part of the data acquisition system used for the measurements.

class-A three-phase PQ analyzer Fluke 1760 compliant with IEC 61000-4-30 standards

Figure 2. Equipment used to obtain measurements for our analysis: (a) PV plant strings; (b) PV plant inverter Kaco Powador 12.0 TL3; (c) pyranometer Kipp&Zonnen SMP3; and (d) PQ analyzer Fluke 1760

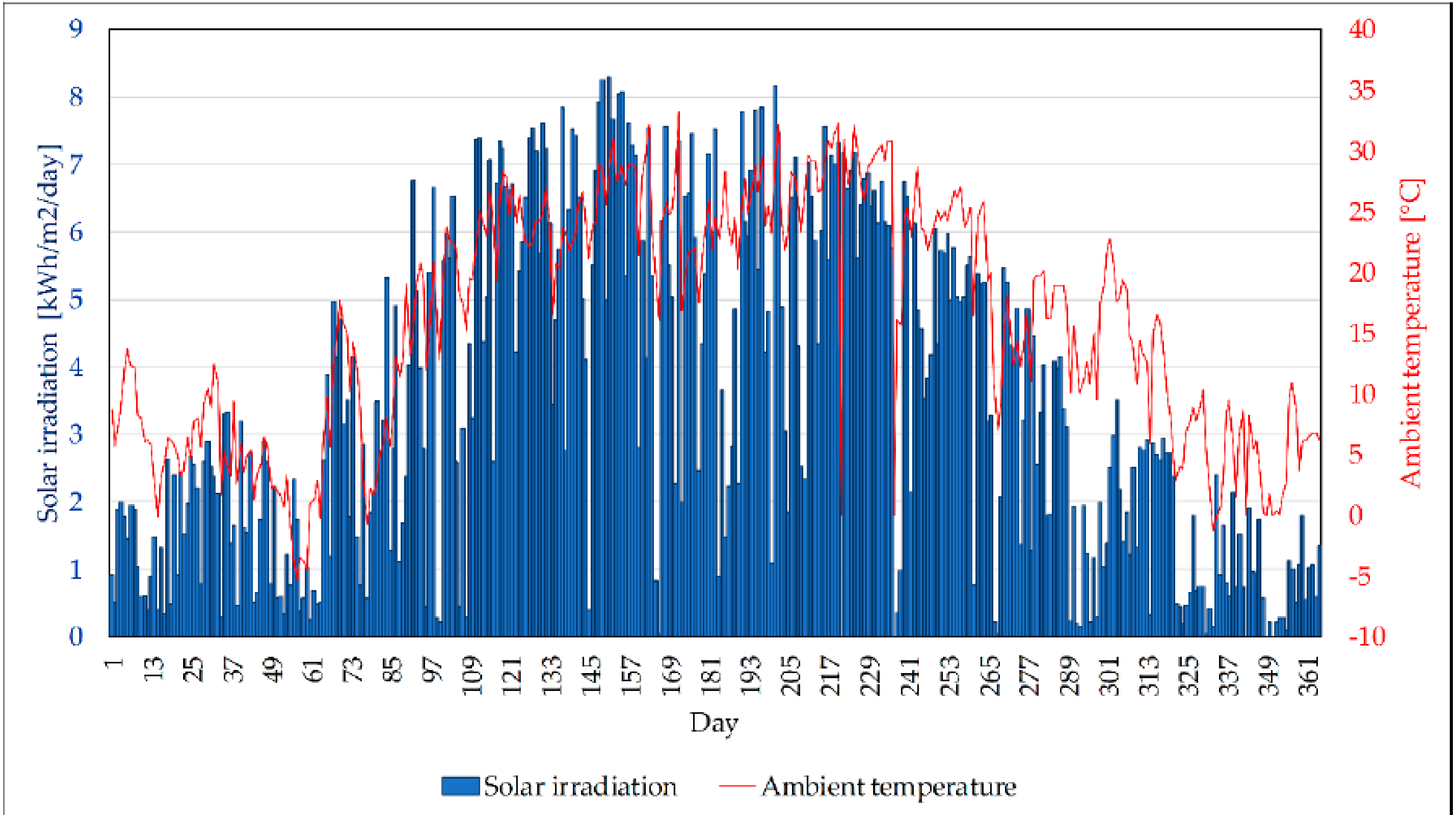


Figure 3. Daily mean values of the solar irradiation and ambient temperatures of 2018.

Meteorological Data

Table 2. Statistical parameters of the solar irradiance and ambient temperatures of 2018.

Parameter	Solar Irradiance	Ambient Temperature
Mean value	175.17 W/m^2	14.65 °C
Minimum value	7.26 W/m^2	−11.21 °C
Maximum value	1172.03 W/m^2	37.16 °C
Standard deviation	248.91 W/m^2	9.76 °C
Coefficient of variation	1.42	0.67

Statistical analysis of the solar irradiance and ambient temperatures, which are later used as input parameters for the MLPNN models

Power Quality Measurement Analysis

The power quality measurements - at the PCC of the PV plant's inverter with the AC distribution grid.

In order to address the problem of the current harmonic prediction, a time series of 1st, 5th, 7th, 11th, and 13th current harmonics on 2 selected days (sunny and partially cloudy days) were analyzed.

The forecasting model predicts the 5th, 7th, 11th, and 13th current harmonic emitted by the PV plant, because it uses a 6-pulse transformerless three-phase grid-tie inverter.
The 6-pulse inverter generates current harmonics of order 6k +- 1 where k represents integer values of which 5th, 7th, 11th, and 13th are the largest.

Erasmus+

e-Lab Prof Eng

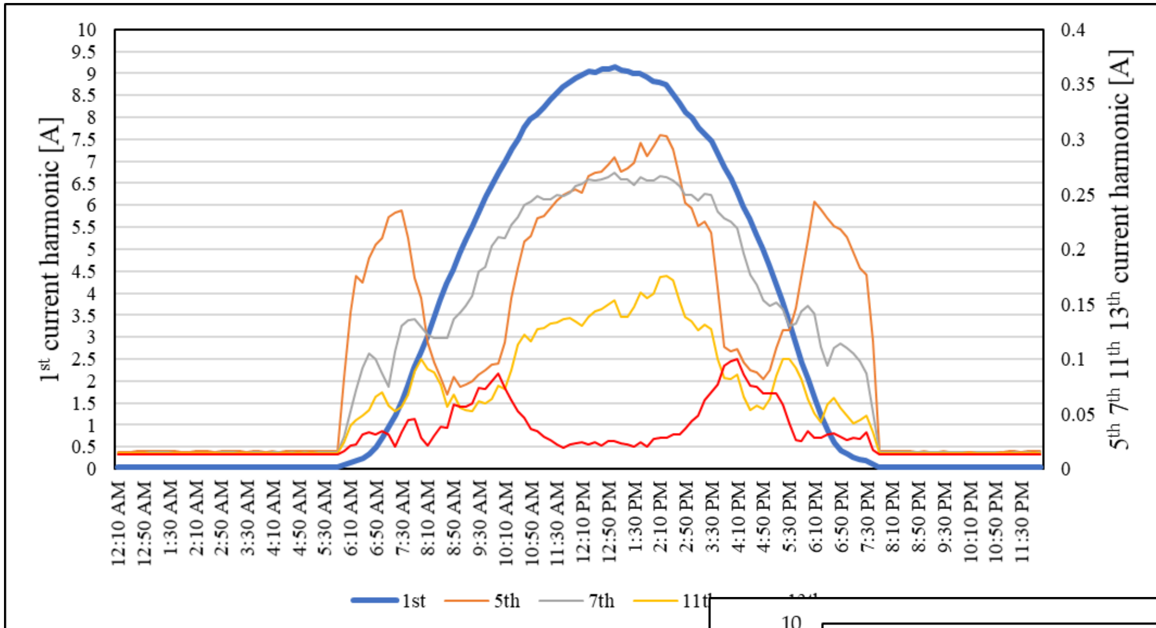


Figure 4. Effective current values of the 1st, 5th, 7th, 11th, and 13th current harmonics during a sunny day (21 August 2018).

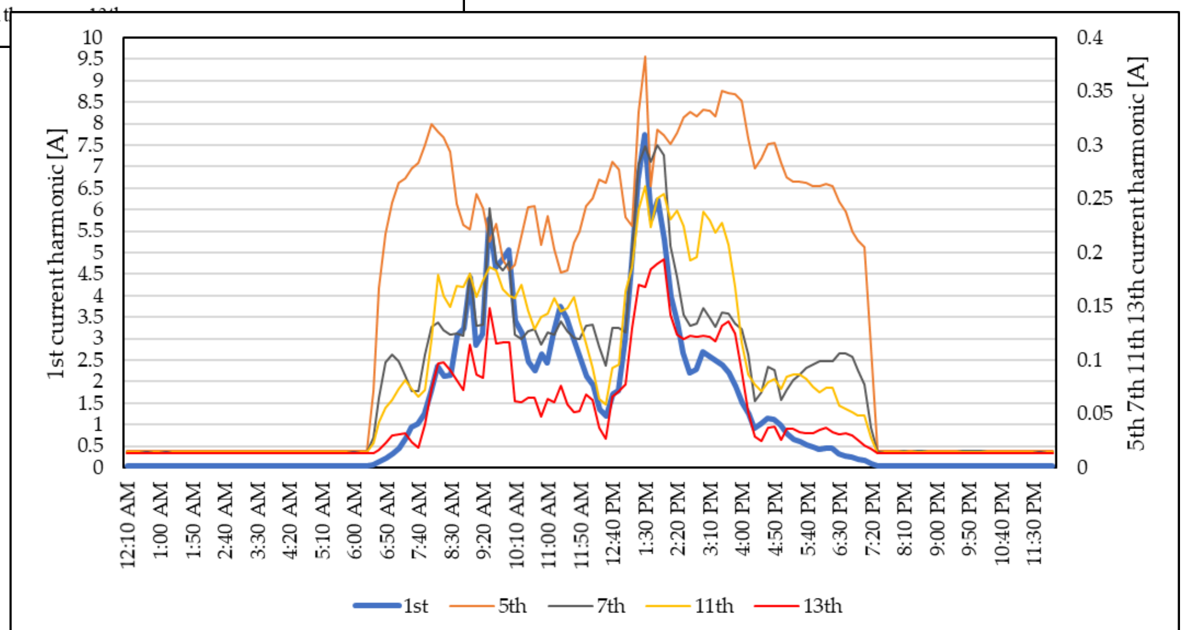


Figure 5. Effective current values of the 1st, 5th, 7th, 11th, and 13th current harmonics during a partially cloudy day (15 April 2018).

A comparison of the current harmonic spectrum for the 2 analyzed days (sunny and partially cloudy days).

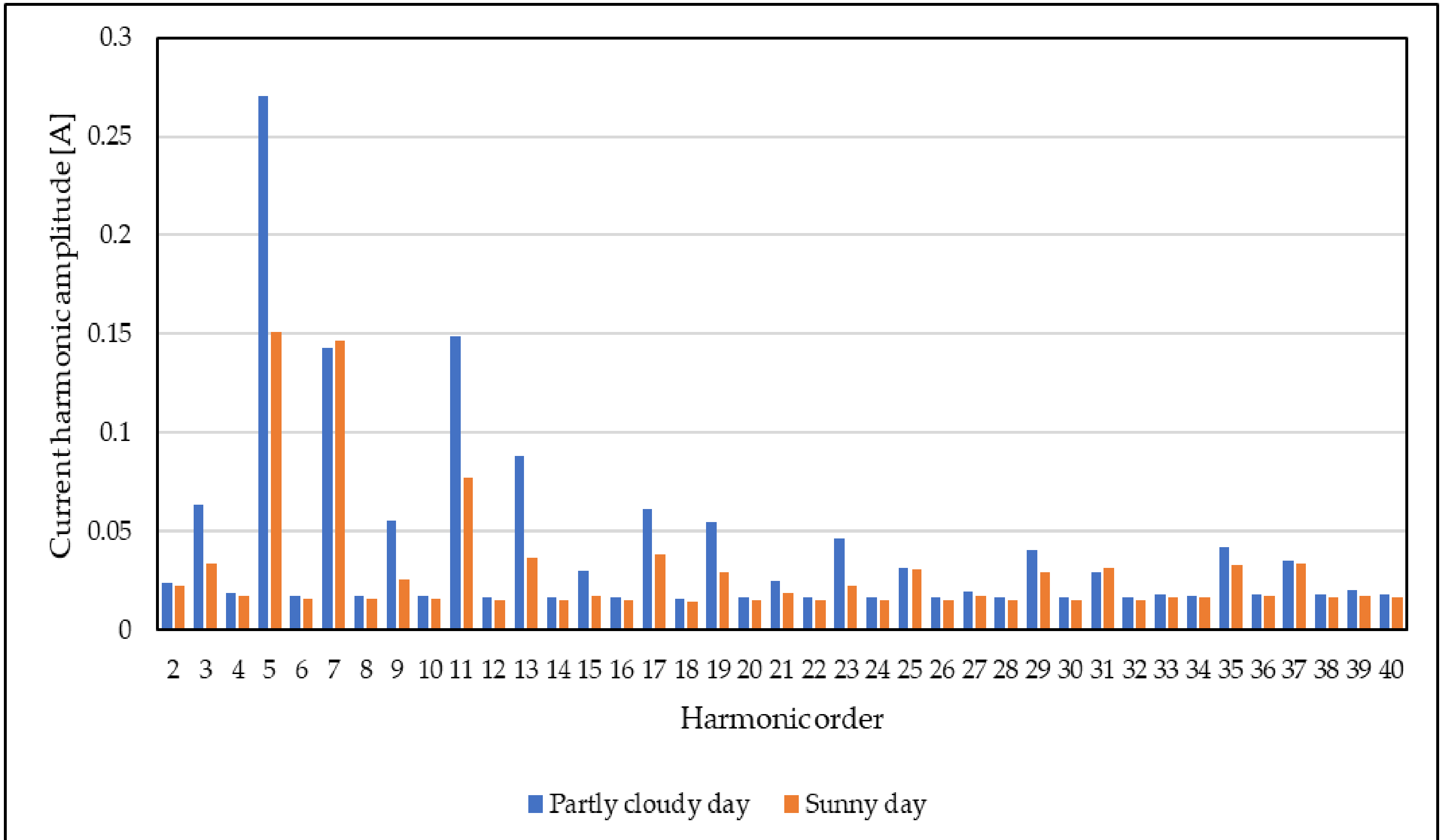


Figure 6. The current harmonic spectrum on a partially cloudy day (15 April 2018) and a sunny day (21 August 2018).

A comparison of absolute THDI calculated from the 2nd to the 40th current harmonic using Equation (1) and the absolute THDI calculated only from the 5th, 7th, 11th, and 13th current harmonics using Equation (2), where *i* represents the order of the current harmonic and I_i represents the effective current of the harmonic order *i*:

$$THDI_{\text{total}} = \sqrt{\sum_{i=2}^{40} I_i^2} \qquad (1)$$

$$THDI_{5\text{-}13} = \sqrt{I_5^2 + I_7^2 + I_{11}^2 + I_{13}^2} \qquad (2)$$

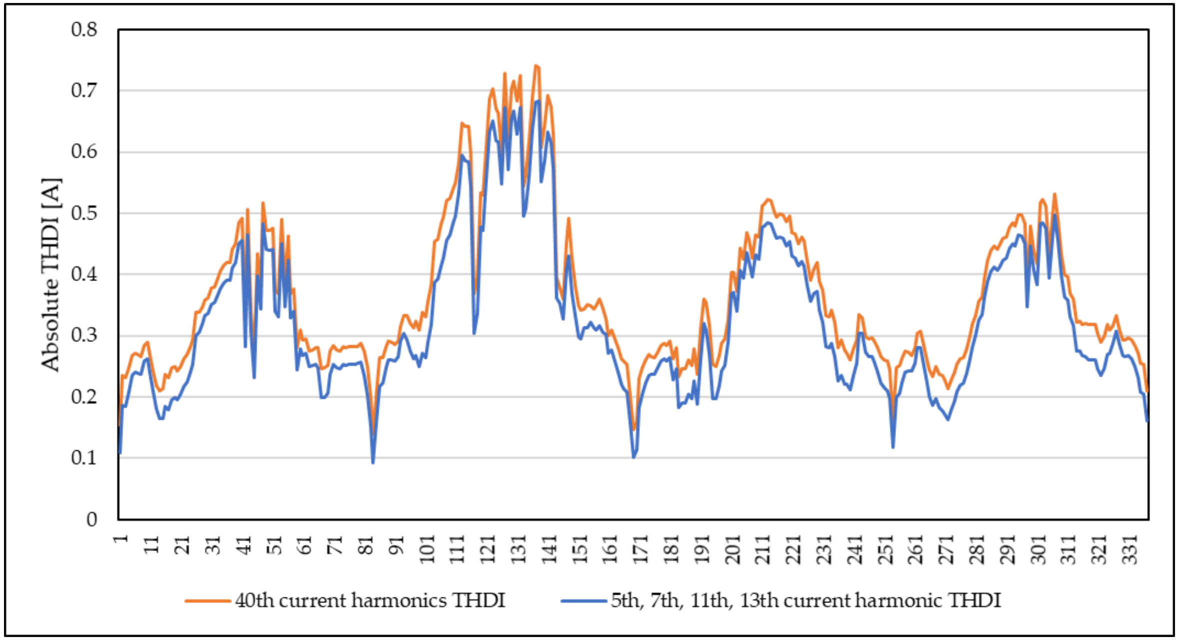


Figure 7. The absolute THDI calculated from the 2nd to the 40th current harmonics and the absolute THDI calculated from 5th, 7th, 11th, and 13th current harmonic.

It is clear that the 5th, 7th, 11th, and 13th current harmonics generate the majority of the THDI.

The annual share of THDI calculated considering only the 5th, 7th, 11th, and 13th current harmonics, calculated as in Equation (2), in THDI calculated considering the 2nd to the 40th current harmonics, calculated as in Equation (1), is **82.04 %**.

Current Harmonics Forecasting with ANN

Performed with **M**ulti**L**ayer **P**erceptron **N**eural **N**etwork (MLPNN)

MLPNN uses **back-propagation** for **training** (learning) – adjustment of synaptic **weights** and **biases** in order to minimise the **error function** – Mean Squared Error (MSE)

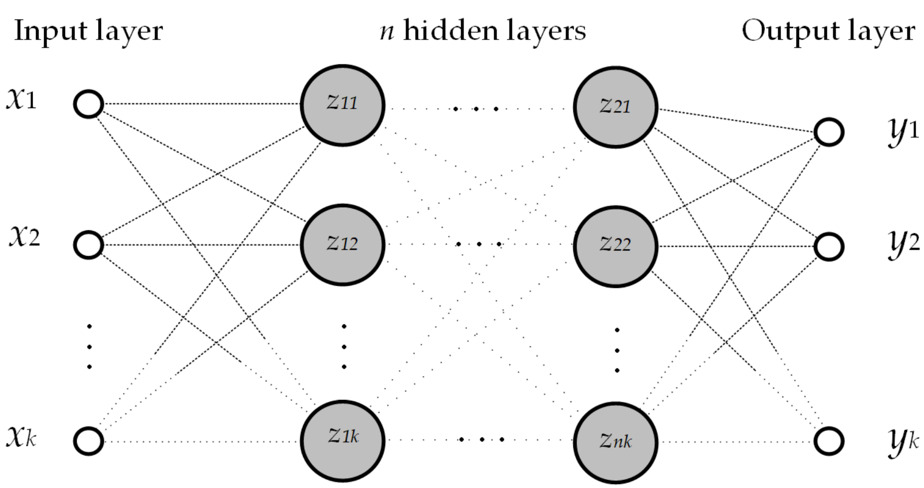


Figure 10. Multilayer perceptron neural network (MLPNN) architecture

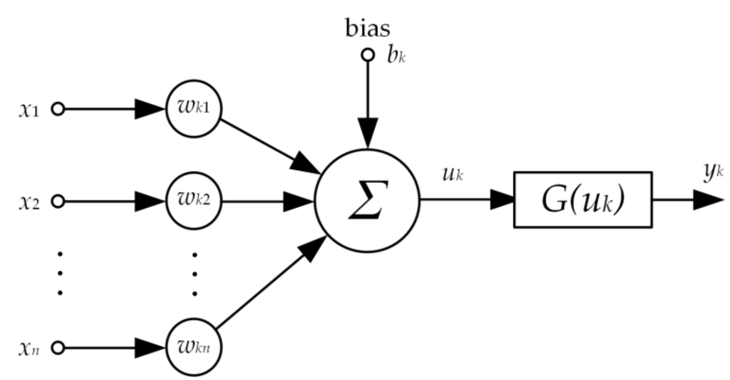


Figure 11. Neuron model diagram

The most challenging problem when modeling an ANN is to determine the **architecture**, i.e., the optimal **number of hidden layers**, **number of neurons** in each layer, and the **activation function** of each layer

Furthermore, an ANN can use different numbers of parameters for **input variables** (predictors) and a different type of **optimizer** for error function minimization (training)

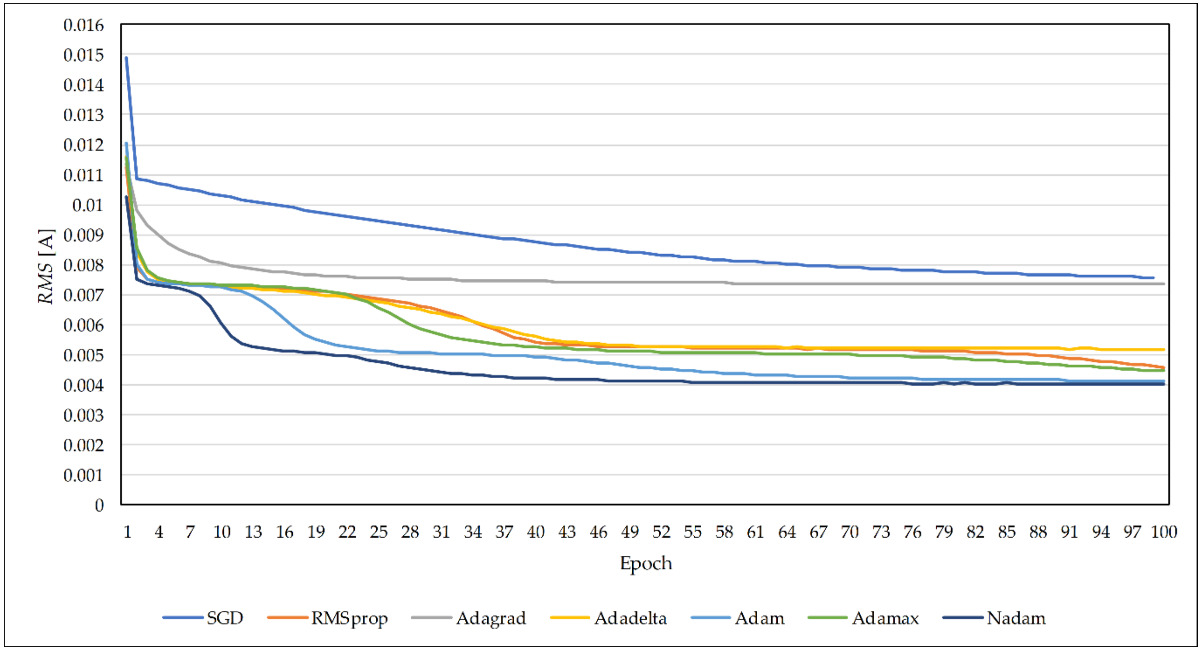


Figure 13. The mean squared error (MSE) of the artificial neural network (ANN) training for different types of optimizers.

Simulations

6 different models are developed using **Keras** library (*TensorFlow*) in **Python** programming language regarding **number of hidden layers**, **number of neurons** in each layer and number of **inputs** (predictors)

Each model **predicts** 5th, 7th, 11th and 13th **current harmonic amplitude** based on input data

Model Name	Input Parameters	Architecture
MLPNN 1	G	1-11-4
MLPNN 2	G, T_{amb}	2-11-4
MLPNN 3	G, T_{amb}, t	3-11-4
MLPNN 4	G	1-11-5-4
MLPNN 5	G, T_{amb}	2-11-5-4
MLPNN 6	G, T_{amb}, t	3-11-5-4

Results

The performance of the MLPNN models was compared with four statistical indices:

- Coefficient of correlation *R*
- Willmott index of agreement *d*
- Root-Mean-Square Error *RMSE*
- Mean Absolute Error *MAE*

The performance results obtained for the six different versions of the MLPNN models show that **MLPNN 6** with **three input parameters** (*G*, T_{amb}, and *t*) and **two hidden layers** produced the **best results** considering the overall accuracy (all four current harmonics)

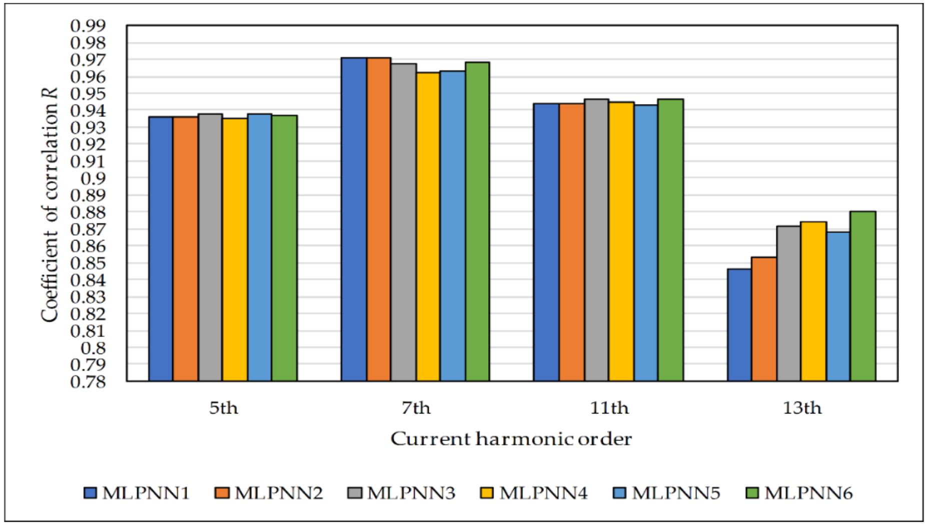


Figure 14. Coefficients of correlation *R* of the predictions of the 5th, 7th, 11th, and 13th current harmonics of the MLPNN models.

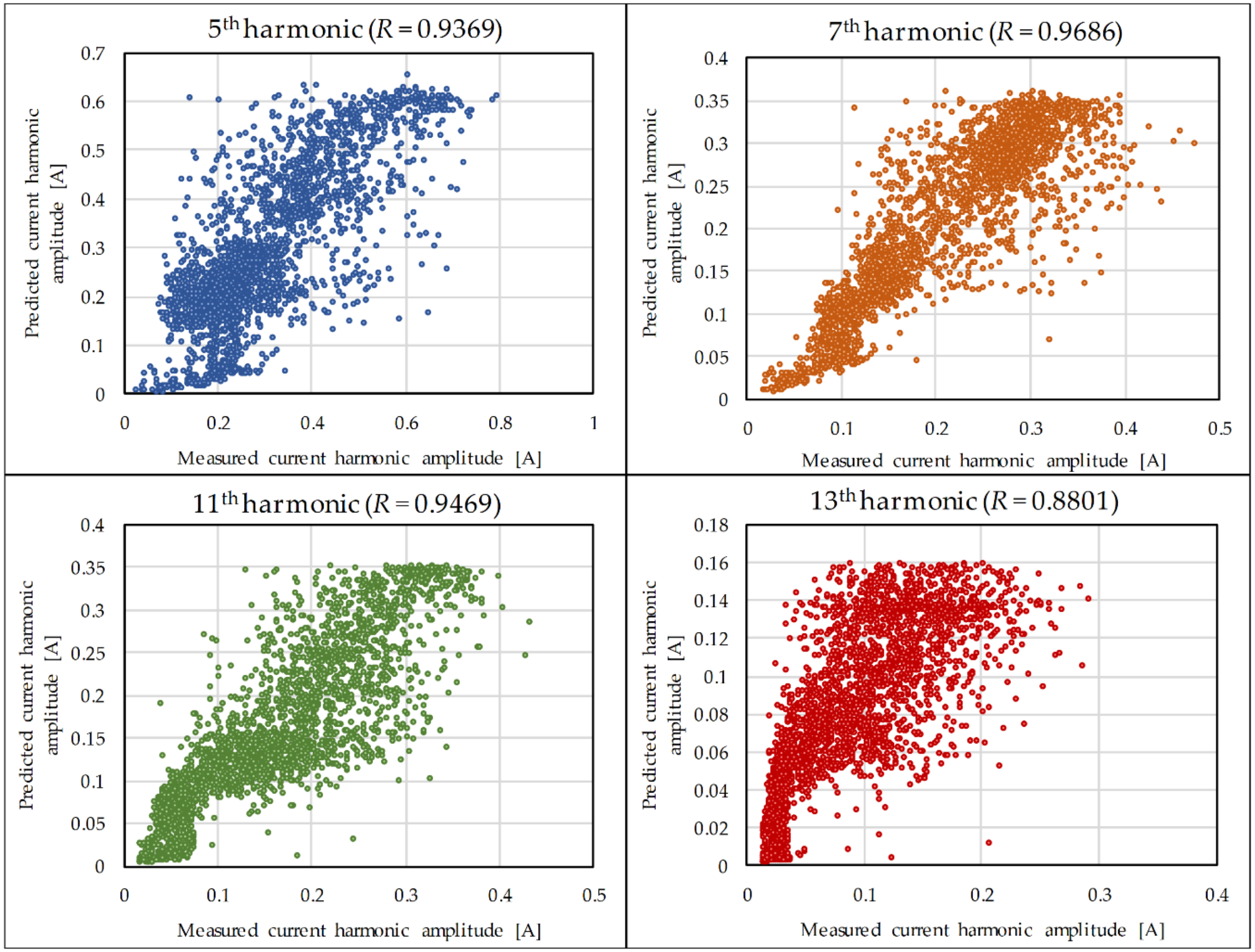


Figure 15. Scatterplots of the measured and predicted current harmonics by the MLPNN 6 model.

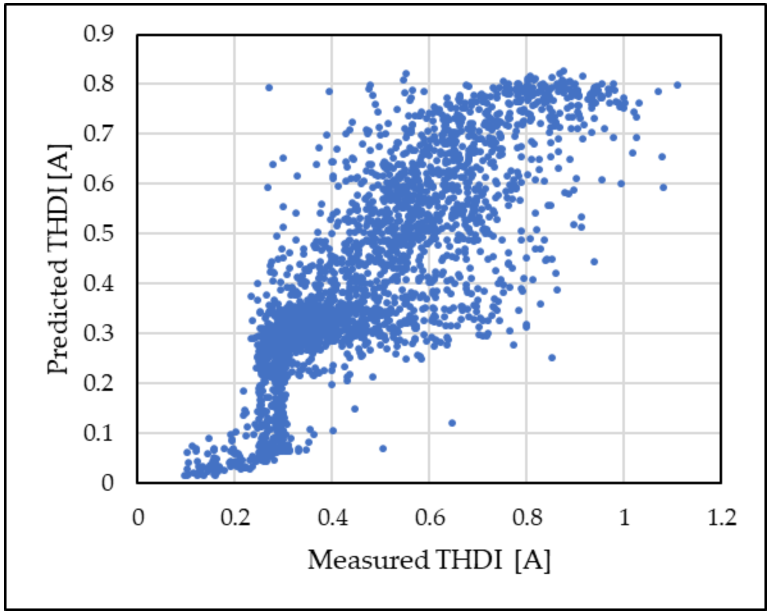


Figure 16. Scatterplot of the measured and predicted THDI by the MLPNN 6 model.

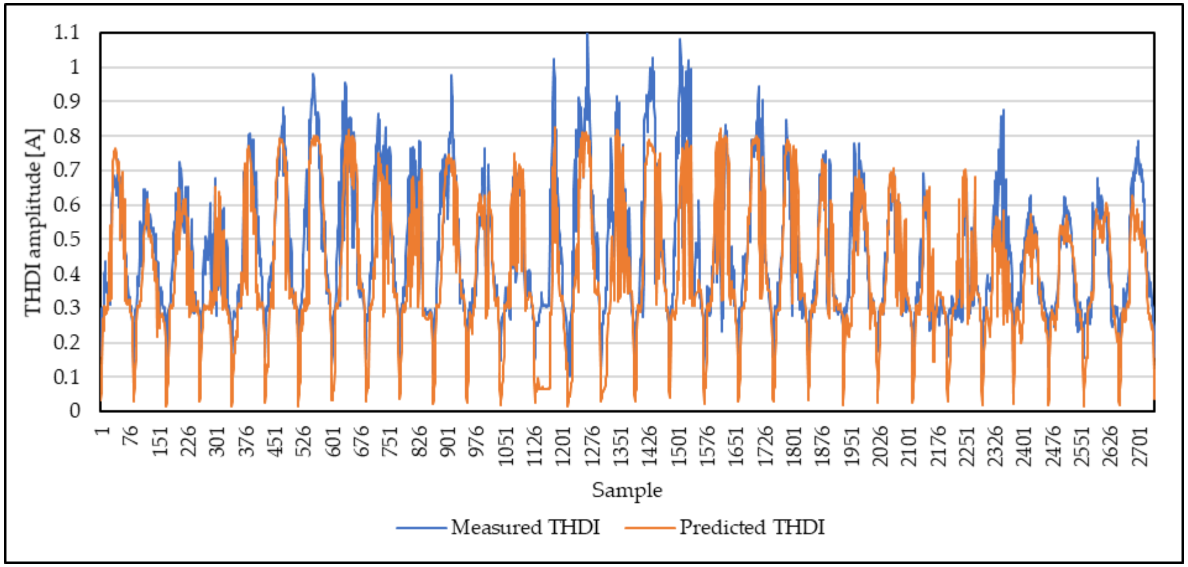


Figure 17. Time series plot of the measured and predicted THDI by the MLPNN 6 model.

Conclusion

The results of the MLPNN model prediction show that the introduction of the third input parameter (time of the day) into the models encouraged slightly better performance.

Furthermore, there was no general conclusion as to whether one or two hidden layers in the MLPNN results in better performance.

This technique can be utilized by the **distribution system operators** (DSO) in order to **predict the current harmonic distortion**, especially in situations of weak radial feeders with high penetration of PV systems. On top of that, DSOs can use this current harmonic prediction model for **monitoring the influence of PV plants' harmonic emissions on system voltage distortion**.

Although the MLPNN models were trained by measurements obtained for a geographical region with a European, humid continental climate, they can be trained for regions with different climates.

Thank you for your attention!