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EFFECTS OF PHOTOVOLTAIC SYSTEMS ON THE BEHAVIOR OF HARMONIC COMPONENTS IN LOW VOLTAGE NETWORK

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ABSTRACT

Renewable energy sources, especially solar systems, have become increasingly important energy sources in recent times. Connecting large PV systems to utility networks can cause a number of operational problems for distribution networks. The extent of these problems depends directly on the percentage of PV penetration and the geographical location of the installation. Possible problems caused by PV systems: over-voltage, output power fluctuation, harmonic distortion, frequency fluctuation. Harmonic distortion is a serious energy quality problem which can occur in photovoltaic systems due to the use of power inverters that convert direct current to alternating current. The resulting harmonics can cause parallel and series resonances, transformer overheating, and protection device malfunctions, which can reduce the reliability of power supply systems.

Keywords: Harmonic distortion, Photovoltaic systems, Harmonic components, Low voltage network, Harmonic analysis

1. INTRODUCTION

Ideally all loads and sources have a pure sinusoidal current waveform. But unfortunately the true waveform of most equipment is very different. Non-linear loads are causing a distortion of the mains voltage.
When we talk about generated harmonics, we always have to think about harmonic currents, because harmonics are generated as currents and most of the troubles are caused by these currents. Without knowing the spectrum of the harmonic current, no usable conclusion can be drawn, yet total harmonic distortion values are usually required. The propagation of harmonic currents in the distribution network causes the formation of voltage harmonics on the busbars [6].

In a common discussion about Harmonics, the difference between current and voltage harmonics is rarely addressed. While current and voltage harmonics are related. The effects are different.

The harmonic currents generated by the nonlinear load, more precisely the currents converted from the basic harmonic to the harmonic by the load, are forced to close through the mains impedances. As a result, harmonic voltage drops are generated at the network elements and harmonic voltages appear at all elements of the entire facility. Harmonic sources sometimes look like voltage generators. If this were true, the impedance of the mains would have no effect on the voltage distortion created on it. In reality, the resulting voltage distortion is (to a limited extent) proportional to the impedance of the supply network, which proves that the harmonic source is a current generator [6].

Voltage harmonics are caused by the current harmonics which distort the voltage waveform. These voltage harmonics affect the entire system not just the loads which are causing them. Their impact depends on the distance of the load causing the harmonics from the power source.

The impedance of the mains supply is usually very small, so the voltage distortion caused by the harmonic current will also be small, often so small that it is lost in the background noise. This can be misleading because it gives the impression that there is no harmonic problem, when in fact the harmonic currents are

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large. The problem is similar to when we want to find a circular current flowing in the ground by measuring voltage. When we suspect harmonics or try to prove that there is none, current must be measured [6].

The following problems can be caused by harmonics on the power grid.

Problems caused by harmonic currents:
- overload of neutral conductors
- overheating of transformers
- incorrectly switching off circuit breakers
- overload of phase correction capacitors
- skin effect [2, 3]

Problems caused by harmonic voltages:
- voltage distortion
- increase in induction motors loss
- problems caused by harmonic currents flowing into the mains
- zero transition uncertainty [2, 3]

The most common nonlinear loads that generate a harmonic current are the following:
- switching power supplies
- fluorescent lamps with electronic ballasts
- uninterruptible power supplies
- variable speed drives [1, 8]

In addition, on the distribution network, the inverters of solar systems that have increased in recent years are also contributing to the rise of harmonic components. This trend will continue to grow strongly in the years to come. In addition, when solar radiation is uneven across the entire solar system, for example, on a cloudy day, much more needs to be regulated to get maximum power out of the system. The charge control circuit constantly monitors and finds the optimal voltage current value for which you can receive maximum power at all times. Or the DC side is not in an ideal state in terms of performance, as due to the rise in temperature of the panels, it can also only be achieved by control to provide maximum performance.

Different THDi levels are generated at the output of the PV inverter in different segments of the solar panels and at different times of the year, depending on the rooftop solar cell generation [7].

2. VOLTAGE QUALITY

The amount and quality of voltage available at the connection point is basically important for consumers. Consumer current flowing through the supply line causes a voltage drop across the line. Due to the time-varying consumer current, the consumer voltage depends not only on the location but also on the time

The quality of the mains voltage depends on a number of parameters, which must be taken into account in order for the consumer's electrical equipment to operate properly and without damage.

The electrical voltage is considered ideal, the voltage signal is a purely sine wave with the voltage and frequency values characteristic of the network grid (Figure 1).

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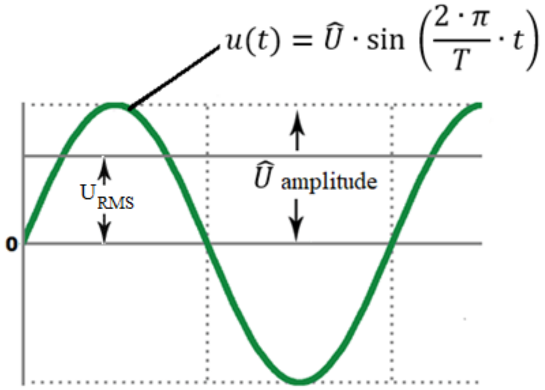

Figure 1. Mains voltage waveform

U_{eff} is the RMS value of the voltage, also known as the root mean square (RMS). In the case of a purely sinusoidal signal, the RMS value can be calculated from the peak value of the signal as follows:

$$U_{eff} = U_{RMS} = \frac{\hat{U}}{\sqrt{2}} \tag{1}$$

In practice, the RMS value should not be determined from the peak value, but should be determined by integrating the time function. Voltage measurements shall be made according to standard real-time RMS measurements. This also applies to the assessment of rapid change [8, 11].

$$U_{RMS} = \sqrt{\frac{1}{T}\int_0^T u^2\,(t)dt} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} u^2\,(\omega t)d\omega t} \tag{2}$$

For digital sampling systems:

$$U_{RMS} = \sqrt{\frac{1}{M}\sum_{s=0}^{M-1}(U_s)^2} \tag{3}$$

The value is calculated from 10 cycles.

M is the number of samples per cycle (M = 256)
Us is the instantaneous value of the voltage at the s-th sampling point.

In power supply practice, to evaluate slow changes, at 50Hz, a real-time average of the measured values over 10 periods should be generated every 10 minutes, and this 10 minute average should be stored [8, 11].

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3. HARMONICS

Ideally all loads and sources have a pure sinusoidal current waveform. But unfortunately the true waveform of most equipment is very different. Non-linear loads are causing a distortion of the mains voltage.

A common feature of nonlinear consumers is that their current drawn from a sinusoidal voltage contains not only the mains frequency component, but also its integer or non-integer multiples [9, 10].

Thus, one way to group consumers is to classify them based on the presence of harmonic current in the consumer current. Based on the above, consumers can be basically divided into two groups:
1. linear consumers
2. nonlinear consumers

The impedance, current, and power of consumers in both groups can be constant or variable over time, and consumers can be symmetrical three-phase or asymmetrical [9, 10].
Harmonic currents are generated by nonlinear electronic loads or non-sinusoidal sources. Harmonic currents flowing through the impedances of the energy system generate voltage harmonics and distort the supply voltage.

The harmonic current is not directly perceived by another consumer, but the harmonic current distorts the voltage through the impedance of the network (due to the rigidity of the network). In this way, we can no longer speak of a completely sinusoidal voltage [8, 11].

3.1. Fourier transform

A periodic function can be produced as the sum of an infinite number of sinusoidal and cosine functions whose circular frequencies are integer multiples of the fundamental circular frequency (the circular frequency of the lowest circular frequency member). The periodic signal is broken down into harmonic components [15].

The vast majority of waveform distortions are characterized by periodicity, i.e., they contain sinusoidal components with frequencies that are multiples of the fundamental harmonic.

The effect of such complex periodic signals (voltages) is can be characterized by the individual effects of harmonic components and the totality of the effects, so we examine it in Fourier order [13, 14, 15].

$$f(t) = F_0 + \sum_{k=1}^{\infty}(A_k cos\, k\omega t + B_k sink\omega t) = F_0 + \sum_{k=1}^{\infty}(F_k cosk\omega t + \rho_k) \tag{4}$$

where the coefficients can be determined as follows:

$$F_0 = \frac{1}{T}\int_0^T f(t)dt = \frac{1}{2\pi}\int_0^{2\pi} f(\omega t)d(\omega t) \tag{5}$$

$$A_k = \frac{2}{T}\int_0^T f(t)cosk\omega tdt = \frac{1}{\pi}\int_0^{2\pi} f(\omega t)cosk\omega td(\omega t) \tag{6}$$

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$$B_k = \frac{2}{T}\int_0^T f(t) sink\omega t dt = \frac{1}{\pi}\int_0^{2\pi} f(\omega t) sink\omega t d(\omega t) \tag{7}$$

$$F_k = \sqrt{A_k^2 + B_k^2} \tag{8}$$

$$\mathrm{tg}\rho_k = -\frac{B_k}{A_k} \tag{9}$$

Thus, with Fourier series decomposition, it is possible to examine the given signal in the frequency range in addition to the time domain. The decremented signal contains the amplitude (usually in decibels) and start phase of each component at a given circular frequency. Harmonics greater than 50 Hz are called harmonics.

3.2. Total Harmonic distrortion

The shape characteristic related to the harmonic analysis is the so-called a distortion factor that characterizes the extent to which a periodic signal deviates from a pure sinusoidal signal. This is also called total harmonic distortion (THD) and is characterized by nonlinearity of the consumer. They are usually given as a percentage [4, 5].

Total voltage distortion:

$$THD_U = \frac{\sqrt{\sum_{k=2}^{K} U_k^2}}{U_1} \cdot 100\% = \frac{\sqrt{U_{2,rms}^2 + U_{3,rms}^2 + U_{4,rms}^2 + \cdots + U_{kmax,rms}^2}}{U_1, rms} \cdot 100\% \tag{10}$$

Total current distortion:

$$THD_I = \frac{\sqrt{\sum_{k=2}^{K} I_k^2}}{I_1} \cdot 100\% = \frac{\sqrt{I_{2,rms}^2 + I_{3,rms}^2 + I_{4,rms}^2 + \cdots + I_{kmax,rms}^2}}{I_1, rms} \cdot 100\% \tag{11}$$

where
- THD_U is the voltage, THD_I is the percentage of current harmonic distortion.
- U_k, I_k is the rms value of the k-th harmonic component
- U_1, I_1 is the rms value of the fundamental harmonic of the voltage
- K is the number of the last harmonic examined,

Harmonic voltages increase the loss of network and consumer equipment, reduce service life, create parasitic torques in electric rotating machines, and interfere with safety, electronic, and IT equipment [4, 5, 8, 11].

According to the MSZ EN 50160 standard, the THD value of the supply voltage must not exceed 8%, calculated up to the number plate of the harmonics 40 [19].

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4. HARMONIC ANALYSIS OF THE PHOTOVOLTAIC SYSTEM

A 25kW photovoltaic system was measured to investigate the behavior of the harmonic components. On the DC side, a total of 92 solar modules are connected to the inverter, each with a power of 265Wp. The number of solar panels within a string is 23 pieces. 4 strings are connected to the inverter with a rated power (AC) of 25kW. The inverter nameplate is shown in TABLE 1. TABLE 2 shows the data for the PV modules.

Table 1. Nameplate of the inverter

AC side output performance (P_{AC})	25 kW
DC side voltage ($U_{DC, MINIMAL} – U_{DC, MAXIMAL}$)	580 – 1000 V
Maximum power point tracking ($U_{MPP, MIN} – U_{MPP, MAX}$)	580 – 850 V
Operate starting voltage ($U_{DC\ START}$)	650 V
Voltage tolerance (ΔU)	+20%; -30%
Maximum current of DC side input ($I_{DC, MAX}$)	44.2 A
Maximum short circuit current of DC side input ($I_{SC, MAX}$)	71.6 A
Maximum performance ($P_{DC, MAX}$)	37.8 kW_p
DC side connections	6 pcs
European efficiency (η_{EU})	98%

Table 1. Nameplate of the Solar panel

Maximum performance (P_{MAX})	265 W
No-load voltage (U_{OC})	38.2 V
Short circuit current (I_{SC})	8.9 A
Maximum voltage during operation (U_{MP})	30.9 V
Maximum current during operation (I_{MP})	8.47 A
Panel efficiency (η)	15.98 %
Serial cells number (N_S)	60 pcs
Temperature coefficient in percentage for U_{OC} (μ_{UOC})	-0.31 %/°C
Temperature coefficient in percentage for I_{SC} (μ_{ISC})	+0.05 %/°C
Temperature coefficient in percentage for P_{MAX} (μ_{Pmax})	-0.41 %/°C

Furthermore, Figure 2 shows the I-U and P-U curves for that module at STC according to the manufacturer's data sheet. The Figure 3 shown the shematic circuit diagram of the examined PV system.

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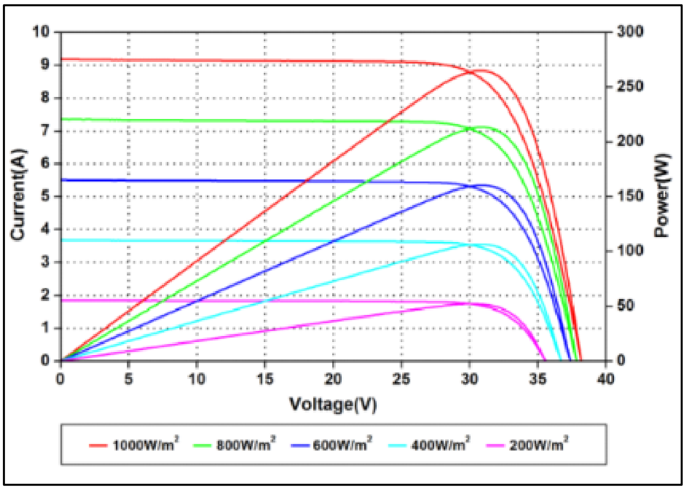

Figure 2. PV module Manufacturer curves

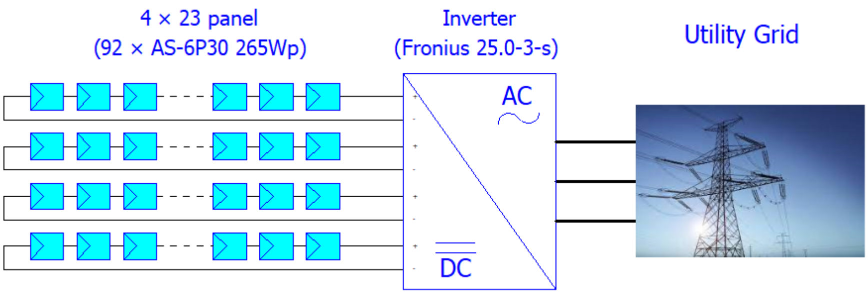

Figure 3. Structure of the examined PV system

This paper used measurements of solar irradiance, the ambient temperature and power quality analyser. The solar irradiance was measured by a PCE-SPM 1 Solar Power Meter. The ambient temperature was measured by Voltcraft K204 digital thermometer digital. The solar irradiance and ambient temperature were recorded every 15 min. The harmonic voltage and current profile examined by using the Chauvin Arnoux C.A 8230 power quality analyser.

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4.2. MEASUREMENT RESULTS

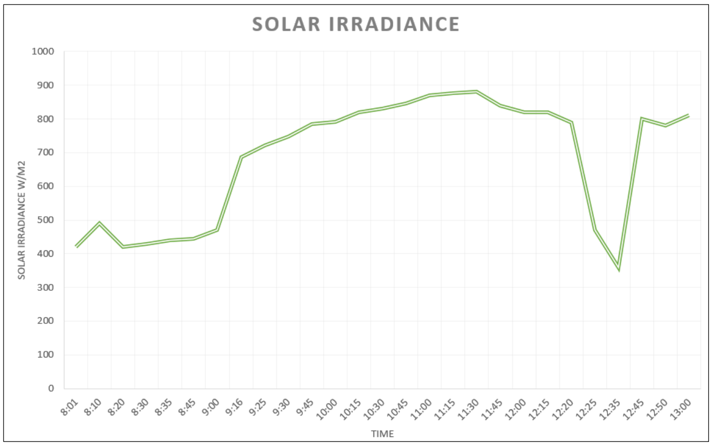

Figure 4. Solar irradiance

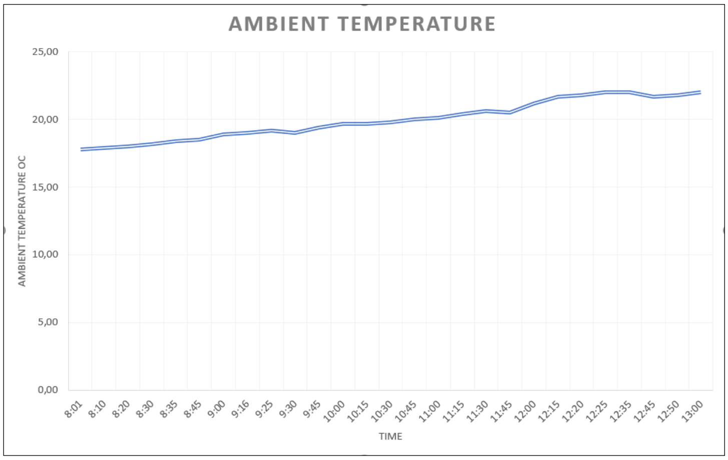

Figure 5. Ambient temperature

Due to the continuously increasing irradiation, the value of THD showed a steady decreasing trend, its value fluctuates less. The value of THD_I ranges from 5.3% to 5.5%. In this case the solar irradiance was from 260 W/m^2 to 400 W/m^2.

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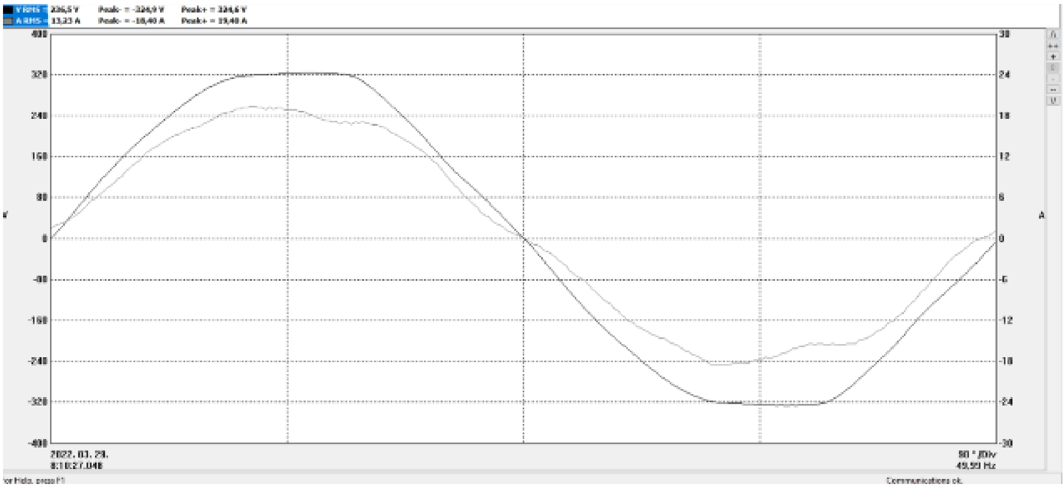

Figure 6. Waveform of voltage and current in case of 260-400W/m2 irradiance

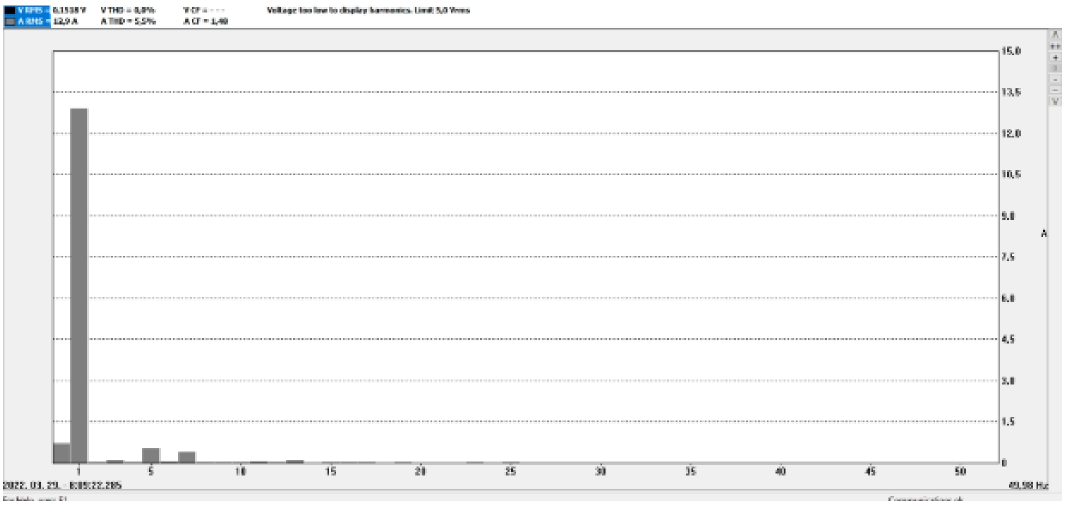

Figure 7. Harmonic components of the current in case of 260-400W/m2 irradiance

Above about 400 W/m^2, the THD_I value decreases further, but its fluctuation increases. It follows an ever-fluctuating trend. THD_I from 3.4% to 6.7% is observed. Which averages 5.05%.

At irradiations between 720-820 W/m^2, the voltage trend remained steady and stable, probably due to the stiffness of the network. The RMS trend of the current fluctuated continuously, which is possible due to the higher temperature of the panels.

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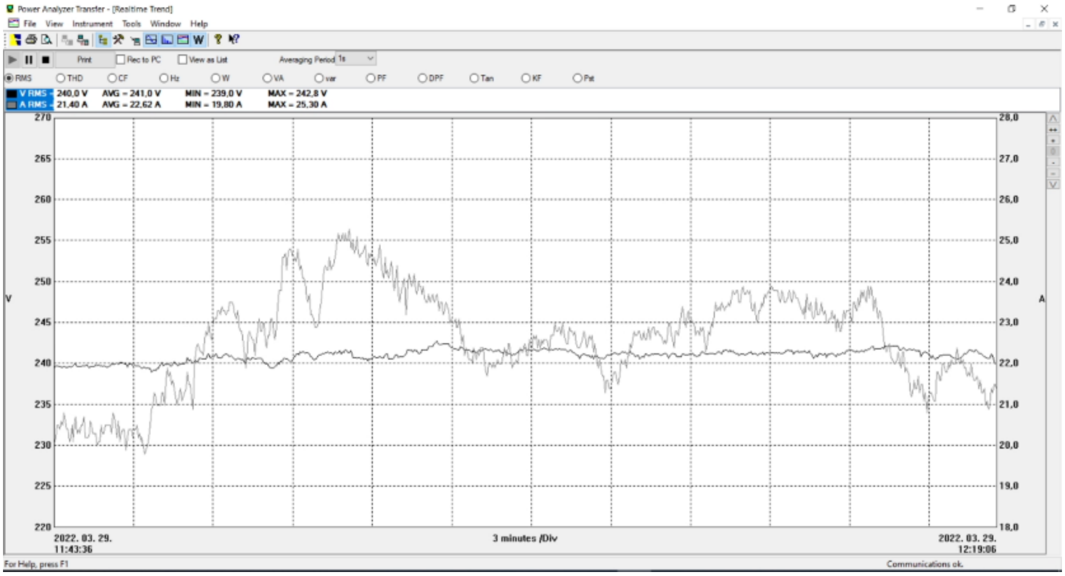

Figure 8. Trend of the RMS value of voltage and current

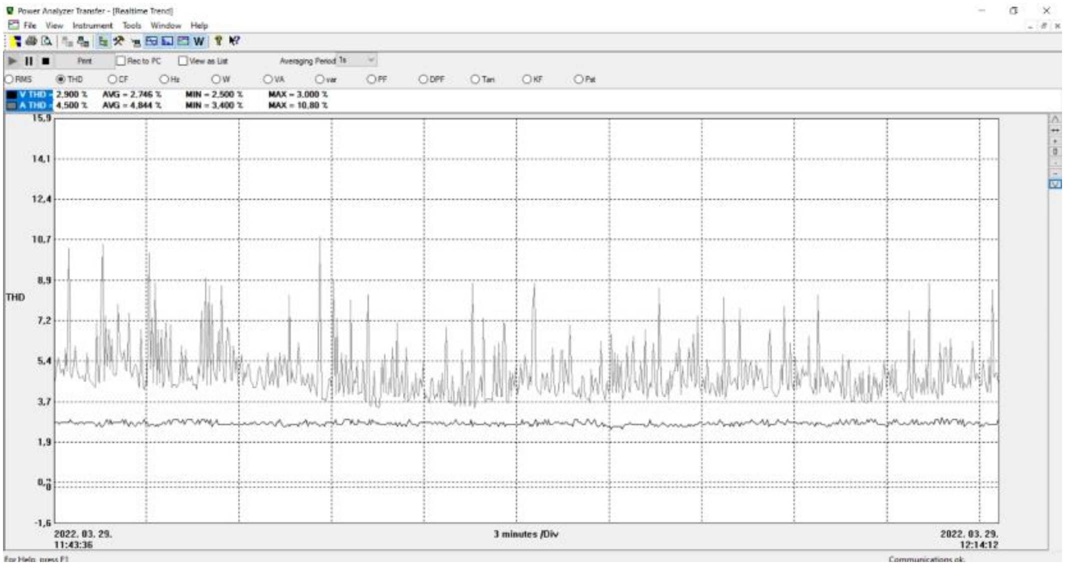

Figure 9. Trend of the THD value of voltage and current

As a result of a small cloud pass, solar irradiation was reduced to 350 W/m^2. In the trend of RMS and also in the trend of THD clearly show that at this stage of production, as system performance has declined, the value of THD will increase during this period (from av. 5-6 % to 14-15%).

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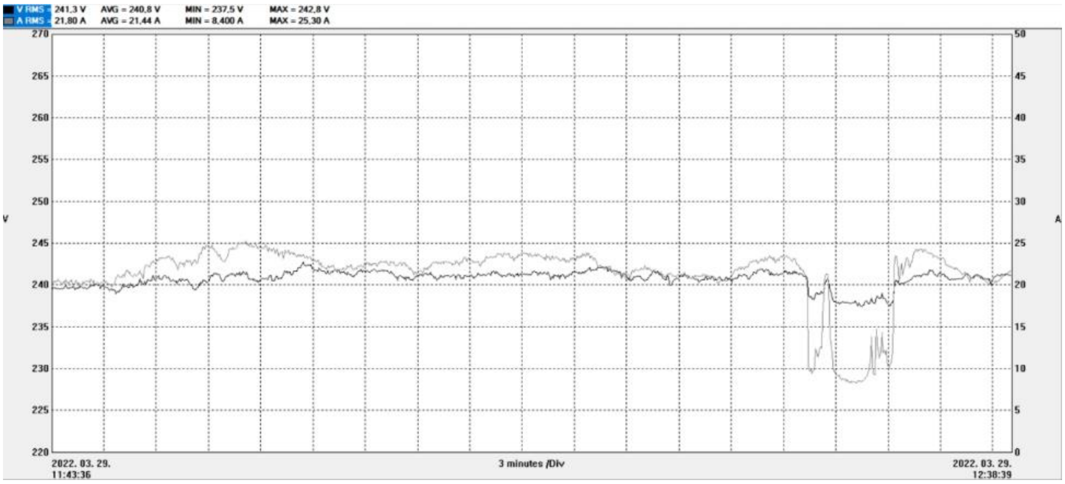

Figure 10. Shadow effect in the trend of current and voltage RMS

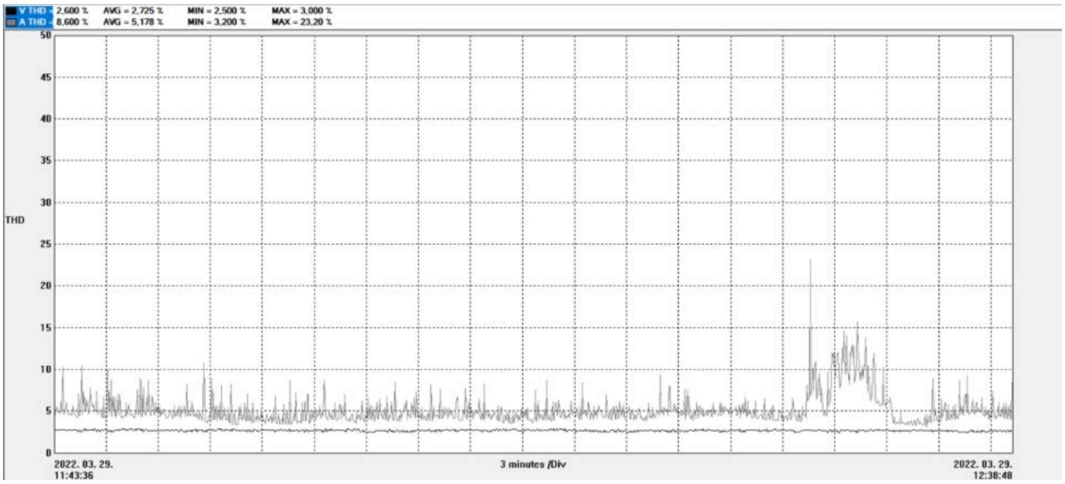

Figure 11. Shadow effect in the trend of current and voltage THD

5. EXAMINATION OF RESULTS IN A SIMULATION ENVIRONMENT

Simulations can predict many more cases and events than measurements. But it is definitely necessary to validate the simulation based on control measurement.

To perform the simulation, the same system was constructed using MATLAB / SIMULINK as the measured system. Regarding the input parameters (for example: irradiation intensity), the same events were measured as those measured during the measurement. Structure of the simulated grid connected PV system shown in Figure 12.

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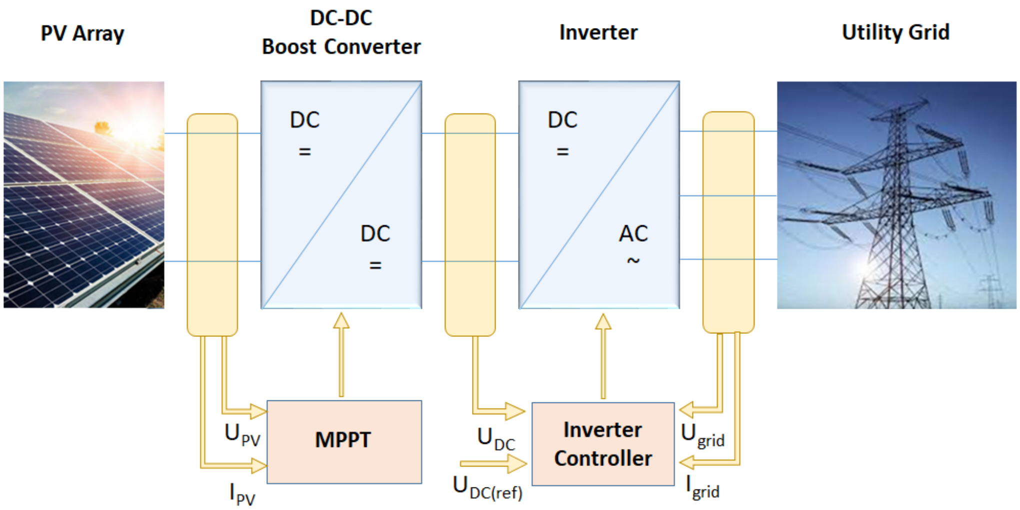

Figure 12. Structure of the simulated grid connected PV system

The P–U and I–U characteristic of the simulated PV array curves are verified through Simulink model under the standard test condition with Gref = 1000 W/m^2 and Trk = 25˚C, as shown in Figure 13.

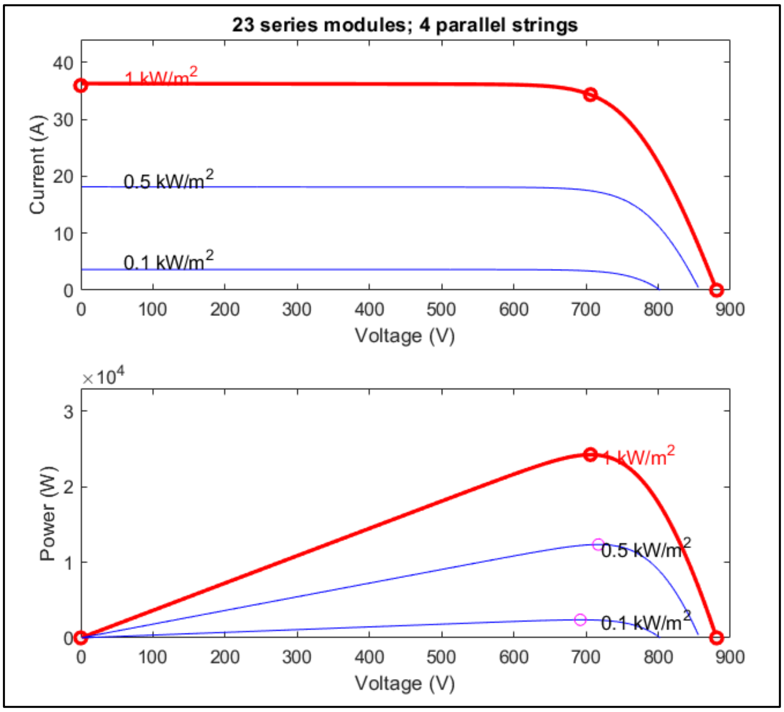

Figure 13. P–U and I–U characteristic of the PV array

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5.1. Comparison of simulated and measured results for validation

The Simulation result shown in Figure 14 is the sinusoidal wave of the grid, that the RMS value of U_{grid} is 236,7 V, when the solar irradiance is 820 W/m².

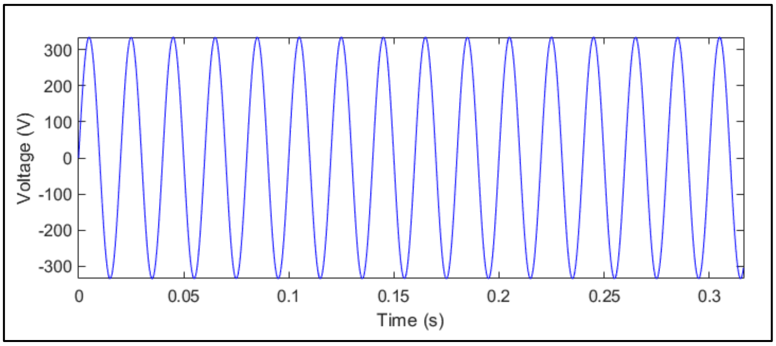

Figure 14. Sinusoidal wave of the simulated grid voltage

This is consistent with the measurement value of 241.0 V, a difference of less than 2% from the measurement value. The difference is mainly due to the different inverter topology used between the simulation model and the actual inverter installed [12].

As shown in Figure 15, the FFT analysis from Simulink shows the THD_I%, which is slightly higher (5,91%) at irradiance 820 W/m^2 compared to the measured data (THDI = av. 5-6%).

As shown in Figure 16 the sinusoidal wave of the grid current from the simulation scope. The RMS value of the grid current is 24,75 A (I_{peak} =35,01 A) which simulate at high solar irradiance of 820 W/m². compared the measured data (I_{RMS} = av. 23-25A).

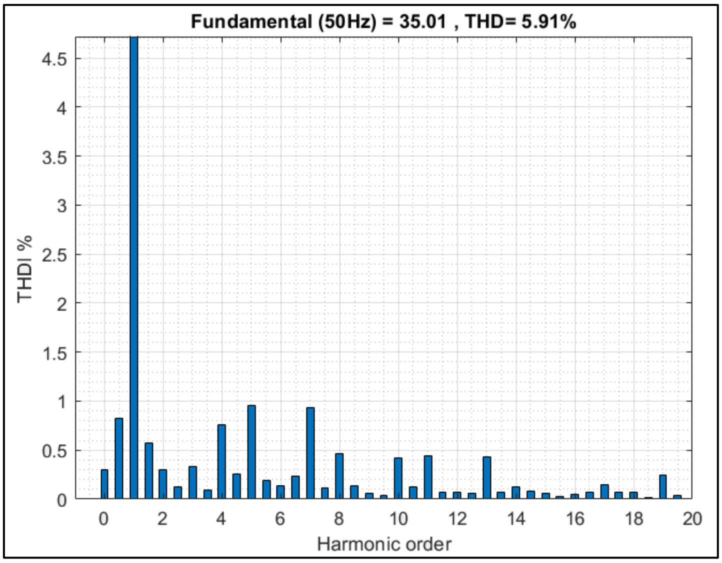

Figure 15. Total Harmonic Distrotion of the current (THDI %) at irradiance 820 W / m²

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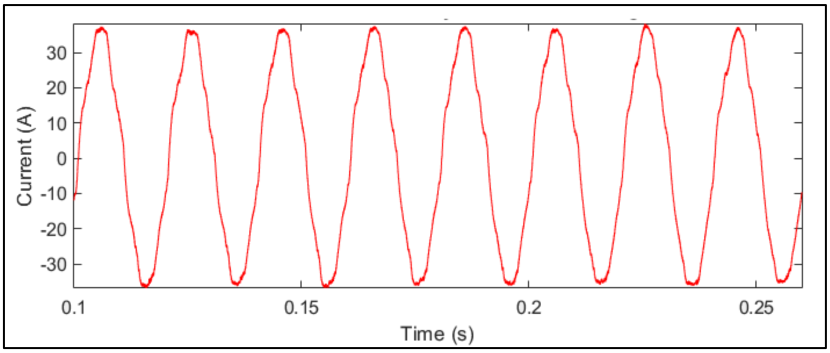

Figure 16. The sinusoidal wave of the grid current at irradiance 820 W / m²

During low solar irradiance as shown in Figure 17, the FFT analysis from Simulink shows the THD_I%, which is relatively higher (15,05%) at 350 W/m² compared to the measured data (THD_I= av. 14-16%).

In the sinusoidal wave of the grid current from the simulation scope in the Figure 18, the RMS value of the grid current is 10,62 A (I_{peak} = 15,03 A) which simulate at low solar irradiance of 350 W/m² compared to the measured data (I_{RMS} = av. 9-11A).

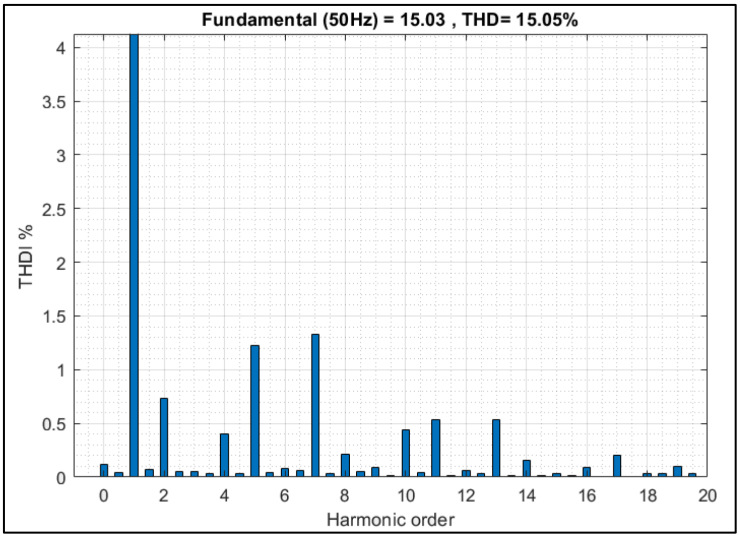

Figure 17. Total Harmonic Distrotion of the current (THDI %) at irradiance 350 W / m²

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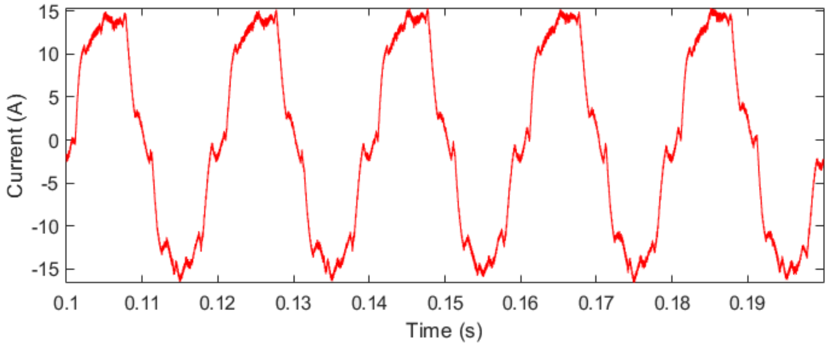

Figure 18. The sinusoidal wave of the grid current at irradiance 820 W / m²

7. RESULTS AND DISCUSSION

The values and the trend are very close in terms of simulation and measurement. This validates the simulation model of the PV system. The difference between the simulation model and the installed actual inverter is due to the different inverter topology. Therefore, it is clear that the THD_I% is high at low solar irradiance level and the output current of a PV module is affected by different solar irradiance levels.

It can be determined from the measurements that not only does the performance of the system decrease as a result of the cloud, but the rate of harmonic distortion also increases. Furthermore, in the measurement, it can be observed that the surface temperature of the solar cells can contribute to the level of harmonic distortion. Since in the morning, when the radiation level rises steadily (for example 300 W/m^2) or a sudden change in irradiance at a daily peak (for example from 800 W/m^2 to 300 W/m^2) is not equivalent in terms of harmonic distortion, even if the irradiance is equal in both cases. This is possible due to the temperature difference between the two cases which can be measured on the surface of the panels.

The results of field measurements and also the simulation show that irradiation has a significant effect on the behavior of harmonics. The voltage and current waveforms, as well as the THD components produced by the solar system, were studied at different levels of solar radiation.

8. CONCLUSIONS

The experimental results were compared with the simulation results. In both cases, if the radiation level of the sun is high, the production of the system is high and the value of the total harmonic distortion is low. However, at low irradiations, the level of total harmonic distortion will be higher.
Depending on the nature of the supply, the amount of load can also affect the total harmonic pollution introduced into the distribution network [7, 16, 17].

In addition, the cumulative THD_I of multiple inverters installed on adjacent buses contaminates the low-voltage network in the current and voltage waveforms with a significant amount of harmonic distortion. Therefore, the harmonic levels of PCC increase due to the nonlinear nature of the output waveforms of solar PV inverters [7, 17, 18].

In addition, the harmonic analysis of nonlinear loads and solar PV across multiple feeders in the LV network would be interesting for future research.

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