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Monitoring Power Quality in Small Scale Renewable Energy Sources Supplying Distribution Systems

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1. Introduction

The integration of renewable sources within the existing power system affects its traditional principles of operation. The renewable energy sources (RES) can be used in small, decentralized power plants or in large ones, they can be built in small capacities and can be used in different locations [1]. In isolated areas where the cost of the extension of the power systems (from utilities point of view) or the cost for interconnection with the grid (from customer's point of view) are very high with respect to the cost of the RES system, these renewable sources are suitable. The RES systems are appropriate for a large series of applications, such as stand-alone systems for isolated buildings or large interconnected networks. The modularity of these systems makes possible the extension in the case of a load growth.

The increasing penetration rate of RES in the power systems is raising technical problems, as voltage regulation, network protection coordination, loss of mains detection, and RES operation following disturbances on the distribution network [2]. The utilization of these alternative sources presents advantages and disadvantages. The impact of the wind turbines and photovoltaic systems on network operation and power quality (harmonics, and voltage fluctuations) is highly important. The capability of the power system to absorb the power quality disturbances is depending on the fault level at the point of common coupling. [3] In weak networks or in power systems with a high wind generation penetration, the integration of these sources can be limited by the flicker level that must not exceed the standardized limits. The wind generators and PV systems interconnected to the main grid with the help of power electronics converters can cause important current harmonics.

2. Power quality and renewable energy sources

Nowadays, the renewable sources generation is rapidly developing in Europe. In the last 17th years, the average growth rate is of wind generation is 15.6% annually [4]. As these renewable sources are increasingly penetrating the power systems, the impact of the RES on network operation and power quality is becoming important. The intermittent character of the wind and solar irradiation constrains the power system to have an available power reserve. Due to the output power variations of the wind turbines, voltage fluctuations are produced. In weak networks or in power systems with a high wind generation penetration, the integration of these sources can be limited by the flicker level that must not exceed the standardized limits.

The photovoltaic (PV) installations, interconnected to the mains supply, can be single-phase connected (photovoltaic installations with capacity less than 5 kW) or three-phase connected (photovoltaic installations with capacity greater than 5 kW). The direct-coupled PV systems, without electrical energy storage, inject in the power system a generated power that follows the intermittency of the primary energy source. In this case, important voltage variations can occur at the PCC. The connection of PV systems to the low voltage grid can determine voltage variations and harmonic currents [5].

2.1. Voltage fluctuations

Determination of voltage fluctuations (flicker effect) due to output power variations of renewable sources is difficult, because depend of the source's type, of generator's characteristics and network impedance. For the case of wind turbines, the long term flicker coefficient P_{lt} due to commutations, computed over a 120 min interval and for step variations, becomes [6]:

$$P_{lt} = \frac{8}{S_{sc}} \cdot N_{120}^{0.31} \cdot k_f(\psi_{sc}) \cdot S_r \quad (1)$$

where N_{120} is the number of possible commutations in a 120 min interval, $k_f(\psi_{sc})$ is the flicker factor defined for angle $\psi_{sc} = \arctan(X_{sc}/R_{sc})$, S_r - rated power of the installation, and S_{sc} - fault level at point of common coupling (PCC).

For a 10 minutes interval, the short-term flicker P_{st} is defined [6]:

$$P_{st} = \frac{18}{S_{sc}} \cdot N_{10}^{0.31} \cdot k_f(\psi_{sc}) \cdot S_r \quad (2)$$

where N_{10} is the number of possible commutations in a 10 min interval.

The values of flicker indicator for wind turbines, due to normal operation, can be evaluated using flicker coefficient $c(\psi_{sc}, v_a)$, dependent on average annual wind speed, v_a , in the point where the wind turbine is installed, and the phase angle of short circuit impedance, ψ_{sc} :

$$P_{st} = P_{lt} = c(\psi_{sc}, v_a) \frac{S_r}{S_{sc}} \tag{3}$$

The flicker coefficient $c(\psi_{sc}, v_a)$ for a specified value of the angle ψ_{sc} for a specified value of the wind speed v_a and for a certain installation is given by the installation manufacturer, or can be experimentally determined based on standard procedures. Depending on the voltage level where the wind generator (wind farms) is connected, the angle ψ_{sc} can take values between 30° (for the medium voltage network) and 85° (for the high voltage network). Flicker evaluation is based on the IEC standard 61000-3-7 [7] which gives guidelines for emission limits for fluctuating loads in medium voltage and high voltage networks. Table 1 reports the recommended values.

Flicker severity factor	Planning levels	
	MV	HV
P_{st}	0.9	0.8
P_{lt}	0.7	0.6

Table 1. Flicker planning levels for medium voltage (MV) and high voltage (HV) networks

The flicker evaluation determined by a wind turbine of 650kW is analyzed. The wind turbine has a tower height of 80 meters, the rotor diameter is 47 m, and the swept area is 1735 m². The electrical energy production during two winter months is 127095 kWh, respectively 192782 kWh. The average wind speeds, measured at 60m height, during the first monitoring month was 6.37m/s while during march was 7.32m/s. The variation of turbine output power is shown in Fig. 1. The intermittent character of the produced power is clearly highlighted. The tower

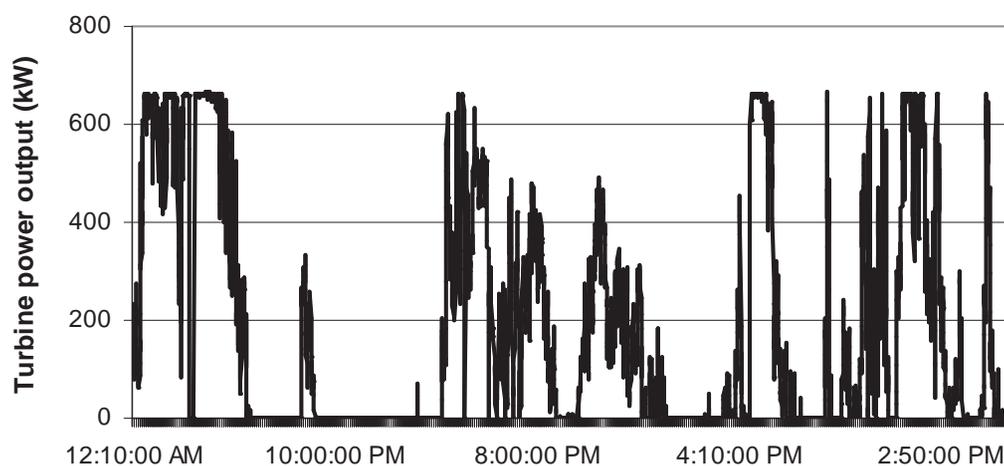


Figure 1. Turbine output power variation during the 1 month monitoring period

shadow effect for the wind generator determines a variation of the absorbed energy, which is measured as a power variation at generator terminals. Fig. 2(a) shows the wind generator, while Fig. 2(b) illustrates the tower shadow effect corresponding variation of the generator output power.

The measured values of the flicker coefficient $c(\psi_{sc}, v_a)$ for different values of the annual average wind speed v_a and for different network impedance angle ψ_{sc} are reported in Table 2. Table 3 reports the flicker coefficient k_f values for voltage step variations, for the same wind generator.

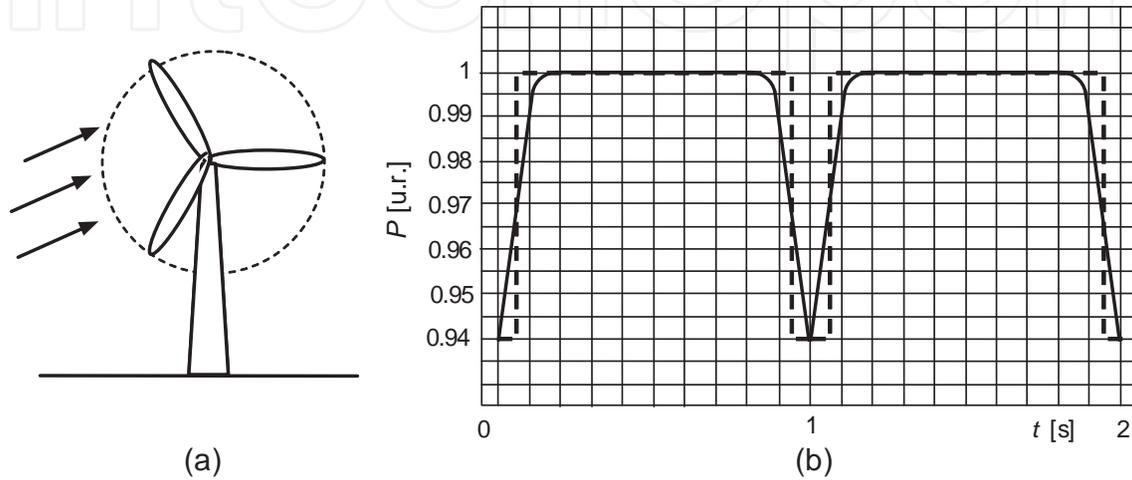


Figure 2. Variation of the wind generator output power due to the tower shadow effect.

Annual wind speed v_a [m/s]	Network impedance angle ψ_{sc} [°]			
	30°	50°	70°	85°
6	3.1	2.9	3.6	4.0
7.5	3.1	3.0	3.8	4.2
8.5	3.1	3.0	3.8	4.2
10	3.1	3.1	3.8	4.2

Table 2. Values of the flicker factor for various values of the wind speed v_a and for various angles ψ_{sc}

		Network impedance angle ψ_{sc} [°]					
		30°	50°	70°	85°		
Flicker factor k_f for voltage step variations	With start at minimum speed			0.02	0.02	0.01	0.01
	With start at rated speed			0.12	0.09	0.06	0.06
Installation is sized for $N_{10} = 3; N_{120} = 35$							

Table 3. Values of the flicker factor k_f

The computations based on the values reported in Table 2 and Table 3 lead to the flicker indicator values:

- i. continuous operation, annual average wind speed $v_a=7.5$, interconnection with the medium voltage network ($\psi_{sc}=50^\circ$, $S_{sc} = 300$ MVA, $S_r = 0.65$ MVA)

$$P_{st} = P_{lt} = \frac{S_r}{S_{sc}} \cdot c(\psi_{sc}, v_a) = \frac{0.65}{300} \cdot 3 = 0.0065$$

2. generator interconnection at minimum speed of the wind turbine

$$P_{st} = 18 \cdot N_{10}^{0,31} \cdot k_f(\psi_{sc}) \cdot \frac{S_r}{S_{sc}} = 18 \cdot 3^{0,31} \cdot 0,02 \cdot \frac{0.65}{300} = 0,00109;$$

$$P_{lt} = 8 \cdot N_{120}^{0,31} \cdot k_f(\psi_{sc}) \cdot \frac{S_r}{S_{sc}} = 8 \cdot 35^{0,31} \cdot 0,02 \cdot \frac{0.65}{300} = 0,00104.$$

2. generator interconnection at rated speed of the wind turbine

$$P_{st} = 18 \cdot N_{10}^{0,31} \cdot k_f(\psi_{sc}) \cdot \frac{S_r}{S_{sc}} = 18 \cdot 3^{0,31} \cdot 0,09 \cdot \frac{0.65}{300} = 0,0049;$$

$$P_{lt} = 8 \cdot N_{120}^{0,31} \cdot k_f(\psi_{sc}) \cdot \frac{S_r}{S_{sc}} = 8 \cdot 35^{0,31} \cdot 0,09 \cdot \frac{0.65}{300} = 0,0047.$$

Due to the output power variations of the wind turbines, voltage fluctuations are produced. Voltage fluctuations are produced due to the wind turbine switching operations (start or stop), and due to the continuous operation. The presented voltage fluctuations study, made for one turbine, becomes necessary in large wind farms as the wind power penetration level increases quickly.

2.2. PV impact on steady state voltage variations

The variability nature of solar radiation, the weather changes or passing clouds can cause important variation of PV output power [8]. The variation of the power produced by a 30kW PV system is illustrated in Fig. 3. Fig. 4 (a) shows the generation power in a sunny day, while Fig. 4 (b) illustrates the generation power in a cloudy day.

The connection of these variable renewable sources can determine a voltage rise at PCC and in the grid. The utility has the general obligation to ensure that customer voltages are kept within prescribed limits. A voltage variation ΔV between V_{max} and V_{min} can appear on short periods. This voltage variation can highly stress the electrical devices supplied by the power system, and in particular the owner of the photovoltaic facility (as shown in Fig. 5). Fig. 5 illustrates the possible case of a summer mid-day, when the load downstream PCC is relatively small and the PV output power exceeds the demand.

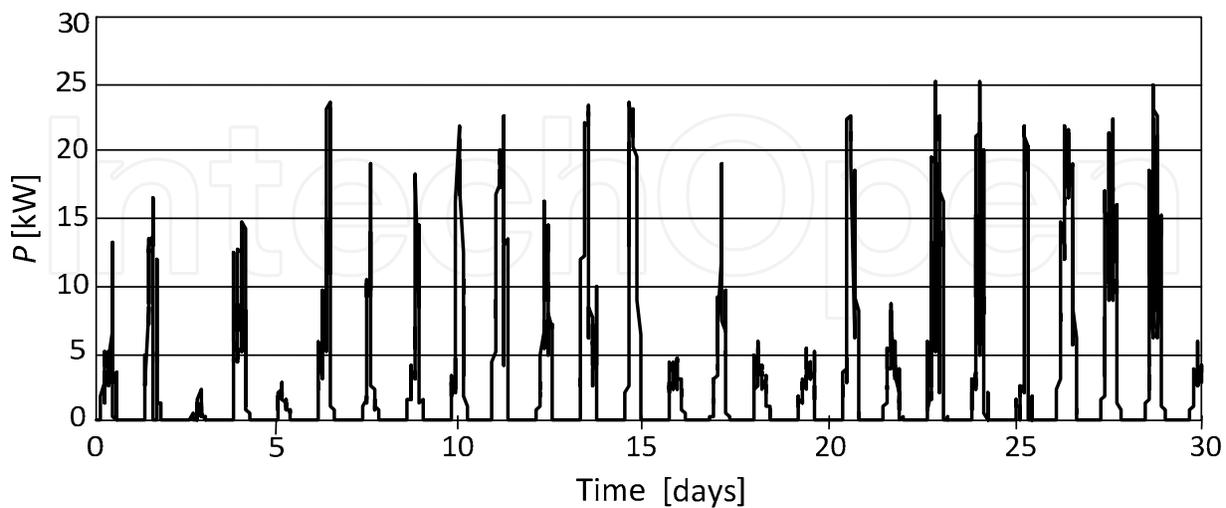


Figure 3. Variation of PV system power output during a month

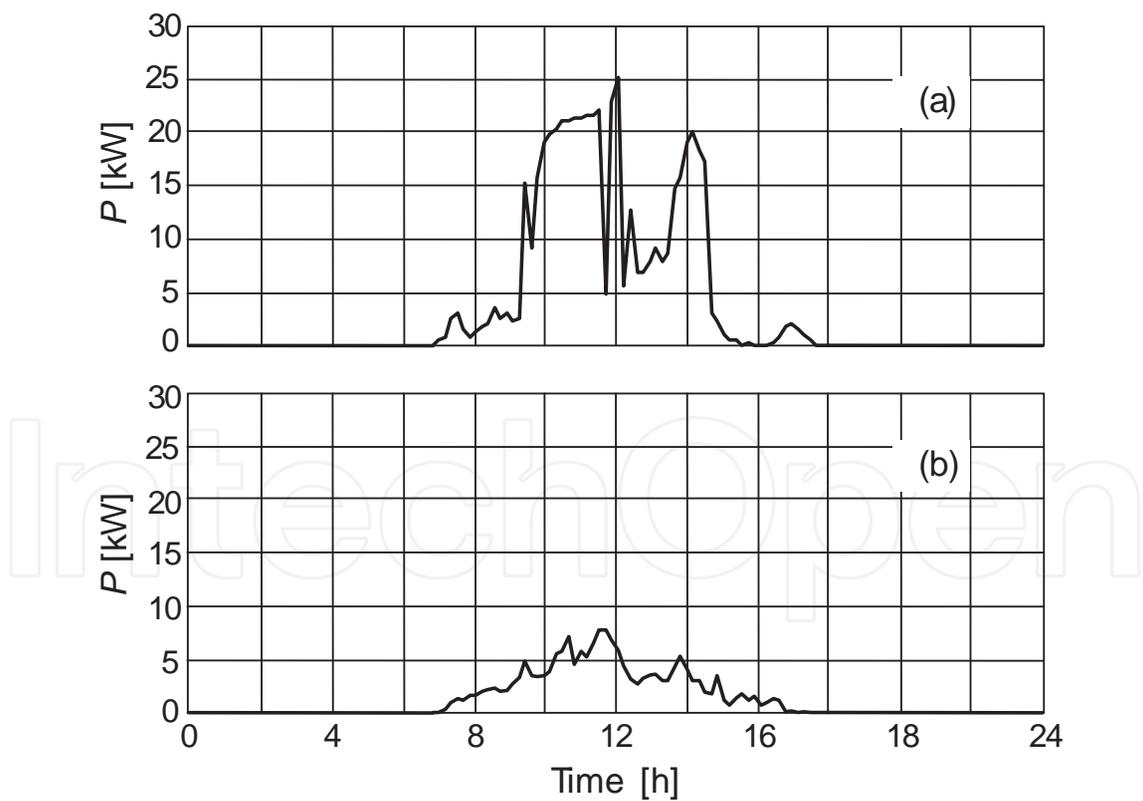


Figure 4. Variation of PV system power output during: (a) sunny day, (b) cloudy day

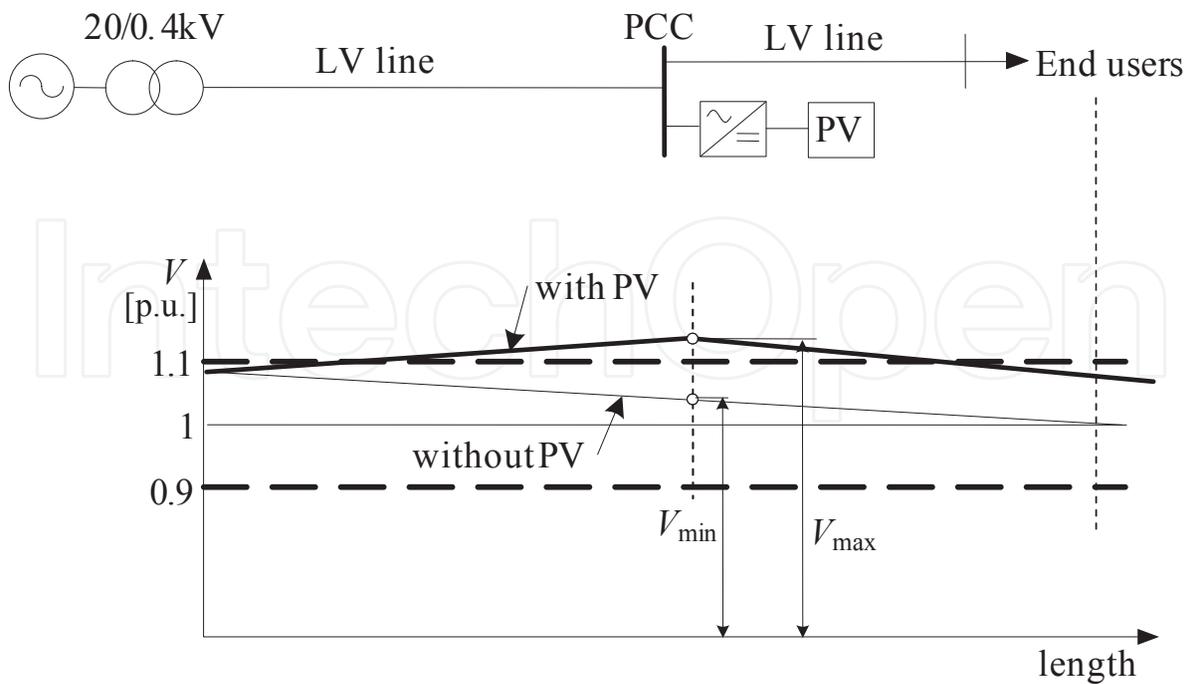


Figure 5. Influence of PV on voltage level

Voltage variations can influence the characteristics of the electrical equipment and household appliances (loss of the guaranteed performances, modifications of the efficiency) leading in some cases even to the interruption of operation. The voltage variation at PCC can be expressed as:

$$\Delta V = \frac{S_{PV}}{S_{sc}} \cdot \cos(\psi_{sc} - \varphi) \quad (4)$$

where S_{PV} is the power produced by PV, S_{sc} is the short circuit power at PCC, $\psi_{sc} = \arctan(X/R)$ is the angle of the network short circuit impedance, φ is the phase angle of the PV output current (we consider that the electric quantities are sinusoidal). In existing power systems, there are measures such that the line voltage to be sinusoidal. In (4), the system harmonics are not considered.

At low and medium voltage levels, the utilities have established limits for the amplitude of the voltage variations, which must not be exceeded during normal operation. Due to the statistical nature of the steady state voltage variations, the standard EN 50160 stipulates statistical limits [9]. In some Countries the limit $\pm 10\%$ established in EN 50160 is applied, while other present guidelines, elaborated in different Countries, impose more restrictive limits for the voltage variations. The relevant variations of the voltage will overlap the voltage's variations caused by load modification and can lead to the widening of the voltage limit bands.

2.3. Current harmonic perturbations

Measurement results of a 200 MW wind farm reveals the harmonic current and voltage spectra, active and reactive power variations, and the relationship between wind farm harmonic emission level and output power. It is considered that the harmonics are determined by the converter at the interconnection point with the main power system. In order to connect the PV power systems with the grid, an inverter that transforms the dc output power of the PV to the 50Hz ac power is required. The small capacity PV systems are interconnected to the main grid with the help of simple single-phase inverters, which can cause important current harmonics. General requirements can be found in standards, especially those for the interconnection of distributed generation systems to the grid and for photovoltaic systems [1, 10]. In the standard IEEE 1547, the harmonic current injection of RES at the PCC must not exceed the limits stated in table 4.

Individual harmonic order	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
Percent (%)	4	2	1.5	0.6	0.3	5

Table 4. Maximum harmonic current distortion in percent of current I , where I is the fundamental frequency current at full system output. Even harmonics in these ranges shall be $< 25\%$ of the odd harmonic limits listed [1].

The current variation on phase a , during one week monitoring period of the 200 MW wind farm, is illustrated in Fig. 6. The high current variability function of wind speed can be clearly observed. The variation of total current harmonic distortion (*THDI*) during the monitoring period is illustrated in Fig. 7. The inverse relationship between the RMS electrical current and *THDI* can be seen in Fig. 6 and Fig. 7, at the same time instants. When the generated power is high (large value of RMS electrical current), the fundamental current is high and the *THDI* is small. For small generated powers, the fundamental current is small and the *THDI* is high. From practical point of view, this fact is not highly important as the small current values do not influence the voltage quality at point of common coupling.

Fig. 8 illustrates the output power variation of a PV system and the total current harmonic distortion variation during a day [11]. When the PV system has an output power close to the rated power, the *THDI* is relatively low. During the shadowing period of the PV system, the *THDI* is taking high values.

The analysis of the total harmonic distortion factor has to consider that, for high variability of the primary energy source, the large *THDI* values can lead to inappropriate conclusions. For the periods with small primary energy source, the electric current injected into the grid presents a reduced fundamental component, resulting in a high distortion factor. As the electrical current has small values, the voltage distortion and the voltage drop in the power system are negligible, and thus the voltage waveform at the point of common coupling is not affected.

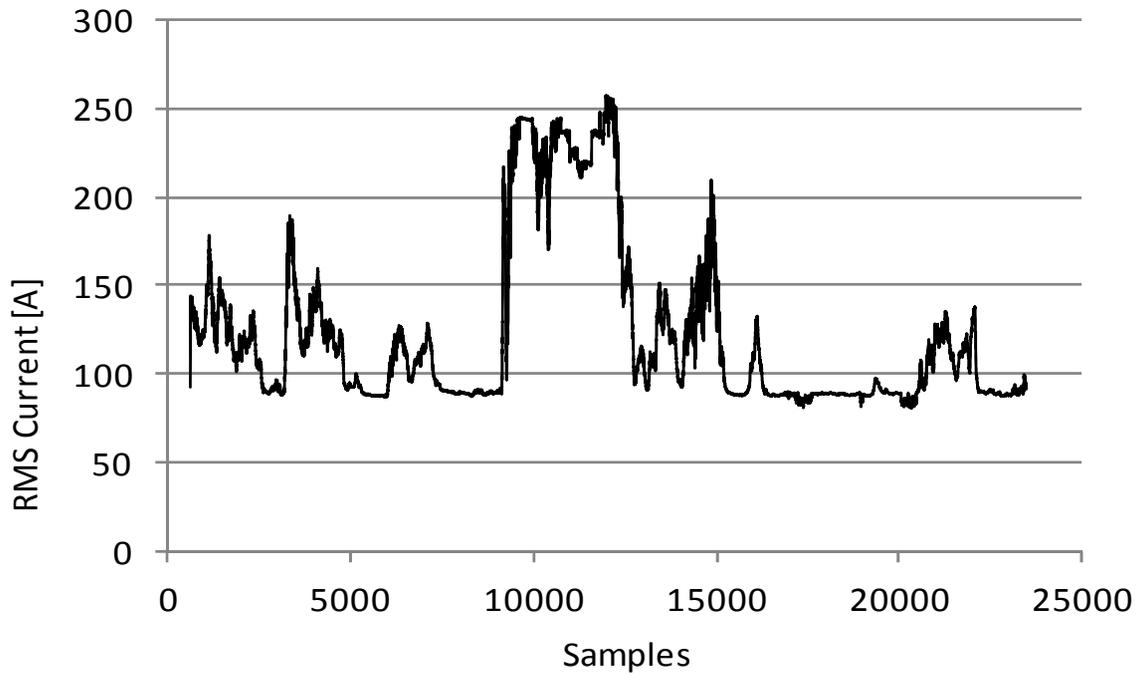


Figure 6. Variation of RMS current, phase a, during the monitoring period

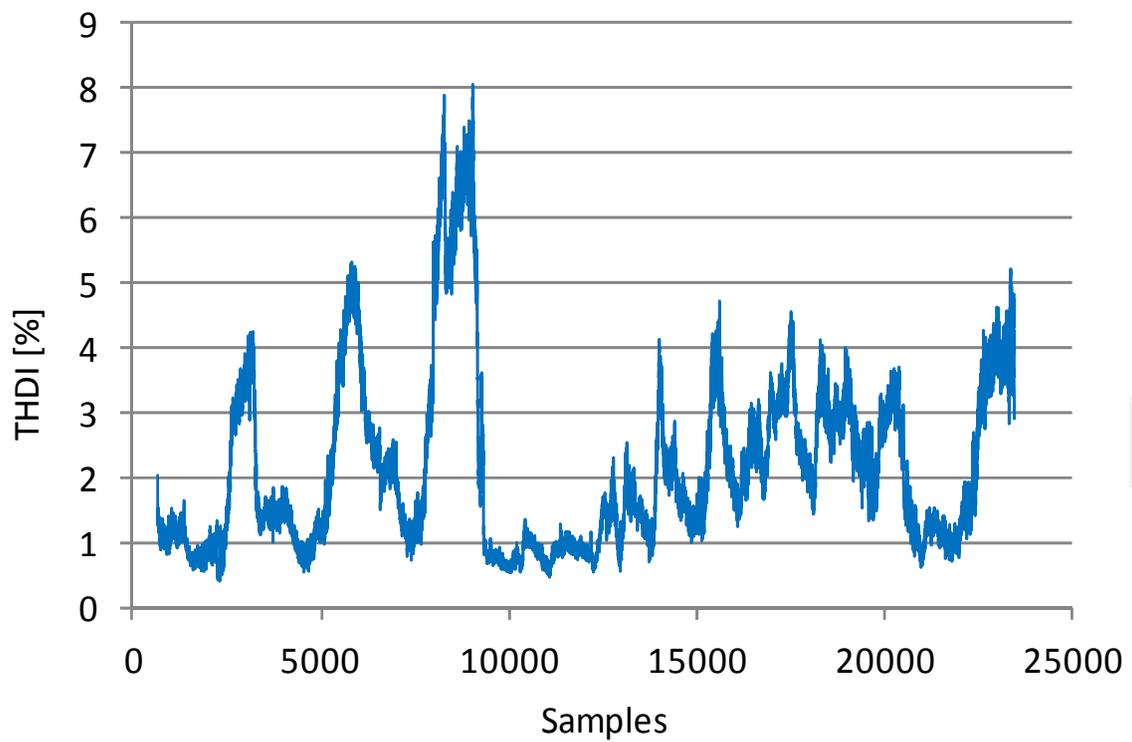


Figure 7. Variation of *THDI* during the monitoring period

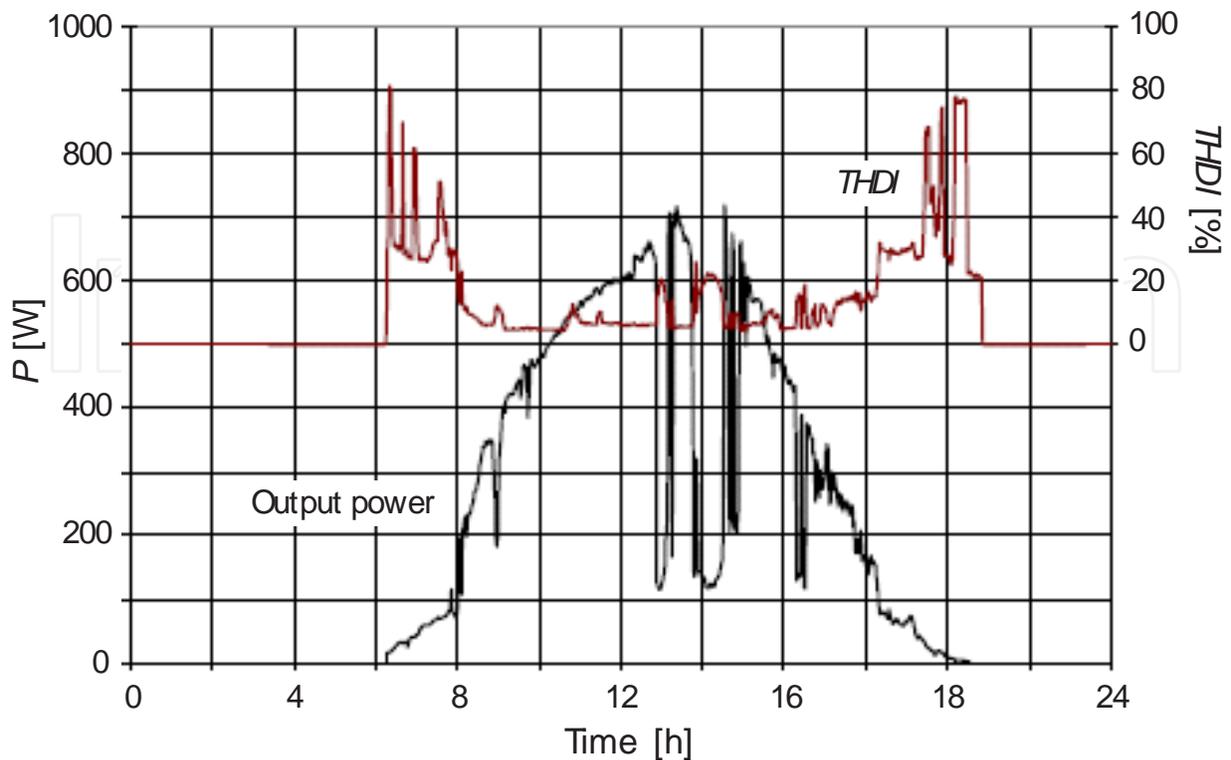


Figure 8. Variation of PV system output power and variation of THDI, during a day.

3. Conclusions

The renewable sources interconnected with the main supply can influence the power quality at the point of common coupling and can pollute the electrical network with harmonic components that must not exceed the stipulated limits. The existing trend of installing more and more small capacity sources implies the establishment as accurate as possible of their impact on power system operation.

The voltage fluctuations determined wind power variations are analyzed, both for the wind turbine switching operations (start or stop), as well as for the continuous operation. The voltage flicker study becomes necessary as the wind power penetration level increases quickly. The connection of variable renewable sources, like photovoltaic systems, can determine a voltage rise at PCC and in the grid which can affect the electrical characteristics of the equipments.

The wind generators and photovoltaic sources, connected to the power system through power electronic converters, can pollute the electrical network with harmonic components that must not exceed the stipulated limits. A better characterization, from the practical point of view, of the total current harmonic distortion determined by renewable energy sources interconnected to the mains supply through power electronic converters is necessary.

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