

## EXPERIMENTAL HARMONIC ANALYSIS AND DISTORTION FACTOR PROPOSAL FOR WIND GENERATION

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*In this paper, the impact on power quality of a wind farm located in south-east of Romania composed of 45 wind turbines is investigated. A field measuring campaign was carried out for a wind farm with a rated power up to 200 MW. Three phase harmonic voltages and harmonic currents, as well as power variations were recorded. The measurements are carried out in different points of the power system supplying the wind farm. The total current generator distortion index (TGDI) is introduced and discussed, as it better quantifies the correlation between generated power and harmonic electric quantities.*

**Keywords:** harmonics, wind farms, distortion, power quality, power factor.

### 1. Introduction

Nowadays, the wind generation is rapidly developing in Europe. In the last 17th years, the average growth rate is 15.6% annually [1]. In the last years, the interest for installing wind turbines in Romania has increasingly growth and a rapid expansion of installed power is achieved, reaching 982 MW at the end of 2011 [1], [2]. In Romania, the request for installing wind turbines is greater than the transmission grid real possibilities to evacuate the produced energy. The intermittent character of the wind constrains the power system to have an available power reserve in order to overcome the turn on/off of the wind turbines [3], [4].

As these renewable sources are increasingly penetrating the power systems, the impact of the wind turbines on network operation and power quality is becoming important [5], [6]. The wind generators can introduce harmonics into the power system, and survey campaign results of harmonic current emissions

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from different wind farms are presented in [7]-[10]. The capability of the power system to absorb this perturbation is depending on the fault level at the point of common coupling. A measurement campaign is conducted for a 200 MW wind farm interconnected to the high-voltage transmission network. The campaign was carried out between August and September 2012.

The paper deals with the measurement results of the investigated wind farm focusing on the harmonic current and voltage spectra, active and reactive power variations, and the relationship between wind farm harmonic emission level and output power. The results reveal that the harmonics generated by the wind farms vary strongly with wind and generated power. In this paper, it is considered that the harmonics are determined by the converter at the interconnection point with the main power system. A new power quality index, the total current generator distortion index (*TGDI*), is presented. The proposed power quality index may better characterize from the practical point of view the current harmonic distortion determined by renewable energy sources interconnected to the mains supply through power electronic converters. The correlation factor between the wind farm power production and total generator distortion index is presented.

Section 2 of this paper describes the wind farm supply layout and gives information about the measuring instruments installed in the four survey points. The measurement results related to power quality analysis are presented in Section 3; the analyses of voltage measurements, current measurements and power measurements are conducted. Section 4 presents the conclusions of the present paper.

## **2. Wind farm supply layout**

The wind farm under investigation, illustrated in Fig. 1, consists of 45 wind turbines, equipped with power electronic converters, and has a rated power up to 200 MW.

Fig. 1 shows the layout of the wind farm interconnection, the technical data of the transformers used in this wind farm, and the measuring points (M1 – M4) of the carried-out survey.

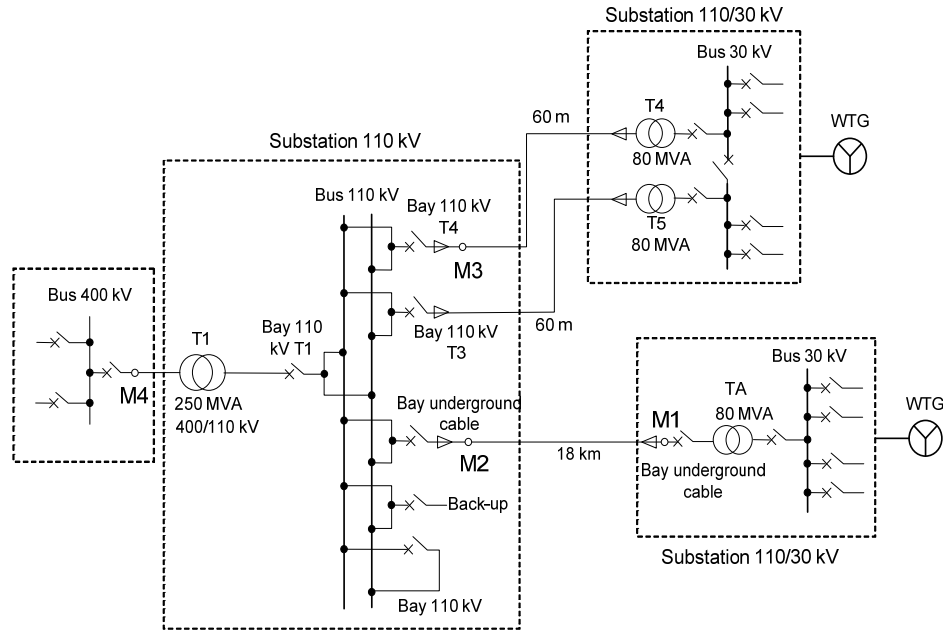


Fig. 1. Layout of wind farms connection scheme

As the purpose of the present paper is to investigate the power quality impact of the large wind farm to the transmission network, the measurement campaign is carried out at the points M1 – M4, using the monitoring equipment reported in Table 1.

The power quality monitoring is carried out at the interface between the wind farms and the transmission grid, as well as at the high voltage transmission grid [11]. All the current and voltage waveforms on the three phases, as well as all the power on the three phases, were recorded. The measuring samples are recorded every 30 seconds.

Table 1

Power system monitoring equipment	
Monitoring point	Power system monitoring equipment
M1	Three-phase Power Quality and Energy Analyzer
M2	Three-phase Power Quality Analyzer
M3	Three-phase Power Quality and Energy Analyzer
M4	Three-phase Energy and Power Analyzer

### 3. Power quality analysis

The variability of the wind determines the power system to have an available power reserve in order to overcome the commutation of wind turbines. The variation of produced power is shown in Fig. 2. The intermittent character of the produced power is clearly highlighted.

The produced wind power, characterized by high randomness, can determine a low power quality with important perturbing emissions in the power systems. Increasing the installed wind capacity, the electromagnetic disturbances can become important.

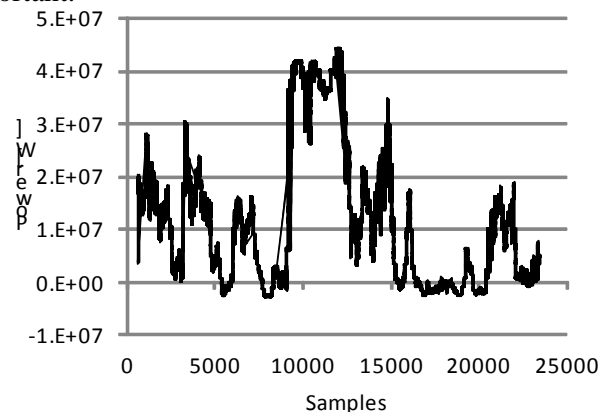


Fig. 2. Wind farm output power variation during the monitoring period

#### 3.1. Analysis of voltage measurements

The RMS voltage variation on phase a, measured at point M1 during the monitoring period, is illustrated in Fig. 3.

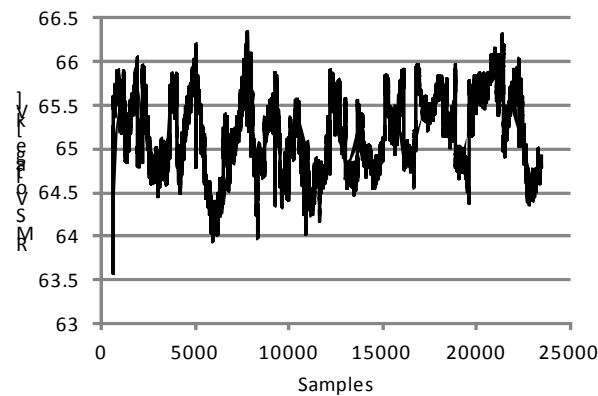


Fig. 3. Variation of RMS voltage, phase a, during the monitoring period

Similar voltage variations were registered on the other two phases. The cumulative probability density function of the voltages can be calculated by applying statistical analysis and is illustrated in Fig. 4. Based on the results shown in Fig. 4, the 95% value of the voltage is 65.8 kV and the 50% value of the voltage is 65.2 kV.

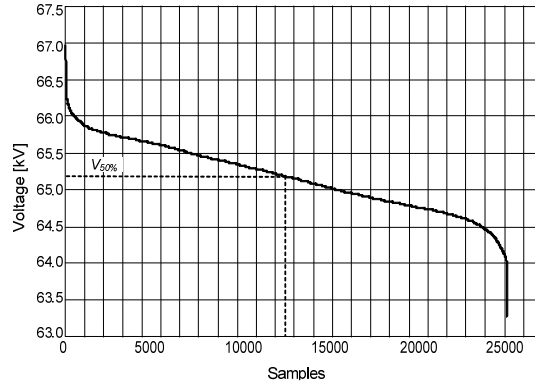


Fig. 4. Calculated cumulative probability function of the RMS voltage at point M1

The variation of voltage total harmonic distortion (*THDV*) expressed by (1), during the monitoring period, measured at point M1, is illustrated in Fig. 5. The values of *THDV* exceeding 4% are measured during the nonfunctional period of the wind generators, when the active load at the substation point M1 is reduced. Most of the time, the values of *THDV* index are around 2%.

$$THDV = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \quad (1)$$

where  $V_h$  is the  $h$ -th order harmonic voltage, and  $V_1$  is the fundamental component voltage.

Fig. 6 shows the cumulative probability density function of *THDV*. Based on the results shown in Fig. 6, the maximum value of *THDV* is 4.82%, the 95% value of *THDV* is 3.32% and the 50% value of *THDV* is 1.79%. As it can be observed, during the monitoring period with low wind speeds (small power production of the wind farm), high values of the voltage total harmonic distortion are registered. During the monitoring period with high power production, the voltage total harmonic distortion does not exceed 4.82%. In accordance with [12], the voltage total harmonic distortion at the 110 kV voltage level is 8%.

The analysis of harmonic spectrum revealed the existence of the 5<sup>th</sup> and 7<sup>th</sup> order harmonics. Fig. 7 illustrates the variation of the 5<sup>th</sup> harmonic voltage level.

The 5<sup>th</sup> order harmonic has an average value of 2.5 % of the fundamental frequency one. The variation of the 7<sup>th</sup> harmonic voltage level is shown in Fig. 8. The 7<sup>th</sup> order harmonic has an average value of 1.8 % of the fundamental frequency value.

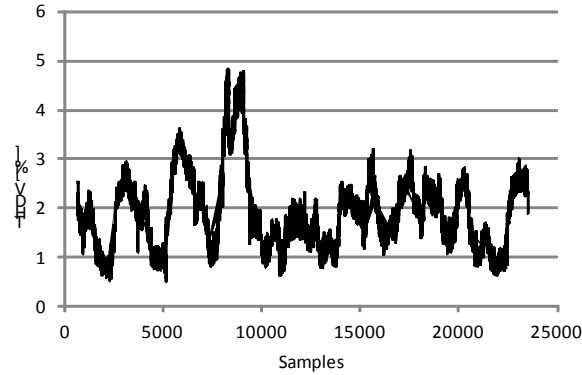


Fig. 5. Variation of *THDV* during the monitoring period

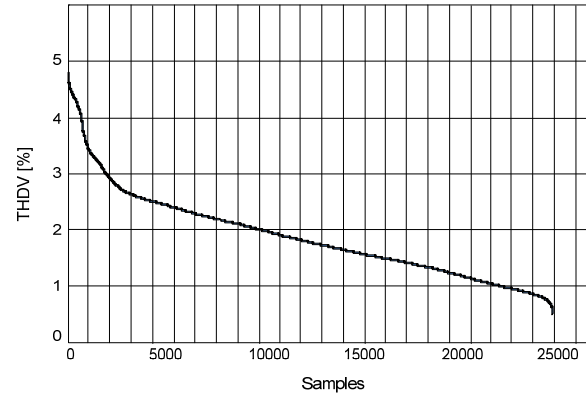


Fig. 6. Calculated cumulative probability function of *THDV*

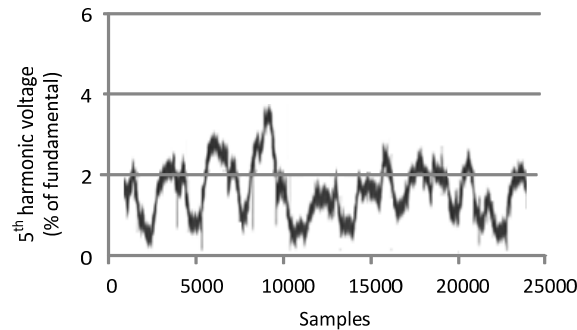


Fig. 7. Fifth harmonic voltage level in percent of the fundamental frequency value

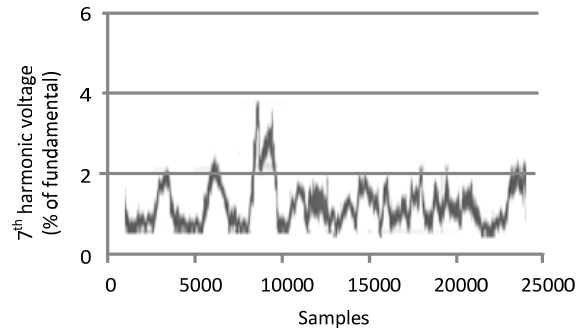


Fig. 8. Seventh harmonic voltage level in percent of the fundamental frequency value

### 3.2. Analysis of current measurements

The current variation on phase  $a$ , during the monitoring period, is illustrated in Fig. 9. The high current variability function of wind speed can be clearly observed.

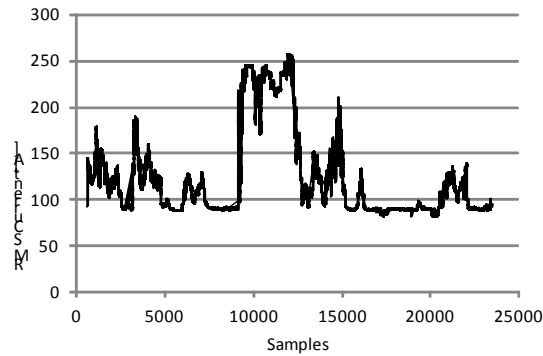


Fig. 9. Variation of RMS current, phase  $a$ , during the monitoring period

The variation of total current harmonic distortion ( $THDI$ ) during the monitoring period is illustrated in Fig. 10. The maximum value of  $THDI$  is 8%, and the minimum value of  $THDI$  is 0.5%. As it can be observed from Fig. 2 and Fig. 10, the high values of  $THDI$  are measured during the low current operation of the wind farm (night period).

The inverse relationship between the RMS electrical current and  $THDI$  can be seen in Fig. 9 and Fig. 10, at the same time instants. This relationship can be observed also in [13]-[15]. 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.

The analysis of current measurements indicates a similar distortion of the current on each phase, mainly determined by the present of the 5<sup>th</sup> (Fig. 11) and 7<sup>th</sup> (Fig. 12) order harmonics.

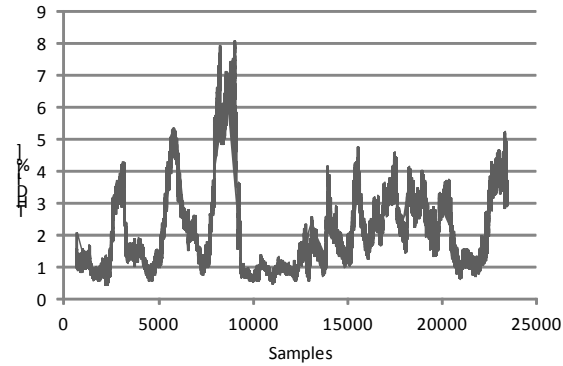


Fig. 10. Variation of *THDI* during the monitoring period

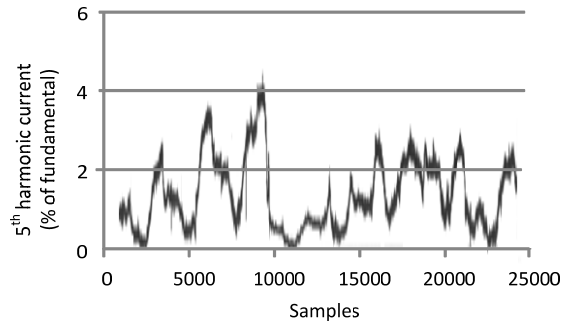


Fig. 11. Fifth harmonic current level in percent of the fundamental frequency value

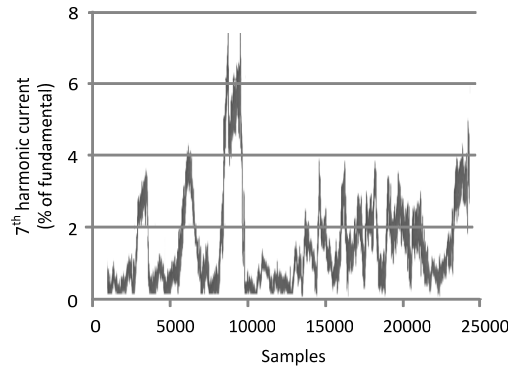


Fig. 12. Seventh harmonic current level in percent of the fundamental frequency value

The analysis of the total harmonic distortion factor has to consider that, for high variability of wind, the large *THDI* values can lead to inappropriate conclusions. For the periods with small wind speeds, 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.

For assessing the operation of wind farms in terms of injected harmonics, the indicator *TGDI* (Total Generator Distortion Index) can be used. This indicator is useful for the high variability sources and can be expressed as:

$$TGDI = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_r} \quad (2)$$

where  $I_h$  is the  $h$ -th harmonic current, and  $I_r$  is the wind farm rated generated current.

The relation between *TGDI* and *THDI* can be expressed as:

$$TGDI = \frac{THDI}{\sqrt{1 + (THDI)^2}} \cdot \frac{I}{I_r} \quad (3)$$

where  $I$  is the measured electrical current.

The variation of wind farm generated power and the variation of *TGDI* are illustrated in Fig. 13.

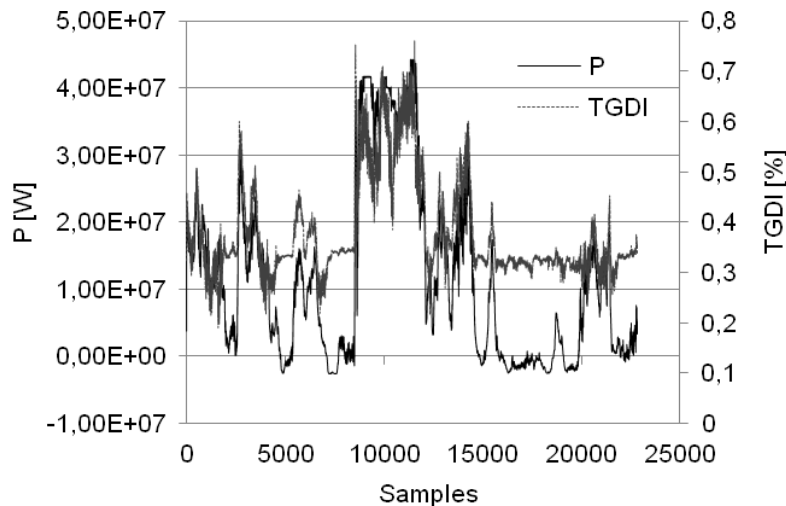


Fig. 13. Variation of wind farm generated power and variation of *TGDI*

The indicator *TGDI* can better define the effect of harmonics into the power grid, with a variation corresponding to the power injected into the network, and which determines the voltage waveform at PCC.

### 3.3. Analysis of power measurements

Based on real power and apparent power measurements, the power factor (*PF*) variation is determined. The power factor should be in the range 0.95 lag and 0.95 lead. Fig. 14 illustrates the variation of power factor, and the variation of *THDI*. The wind speed influence is clearly observed. The monitoring period characterized by low generated power and small amplitude currents, but highly perturbed, reveals the low power factor. The monitoring period with high amplitude currents determines a high power factor. During the monitoring period when the wind speed is high, the power factor reaches the maximum value of 0.9.

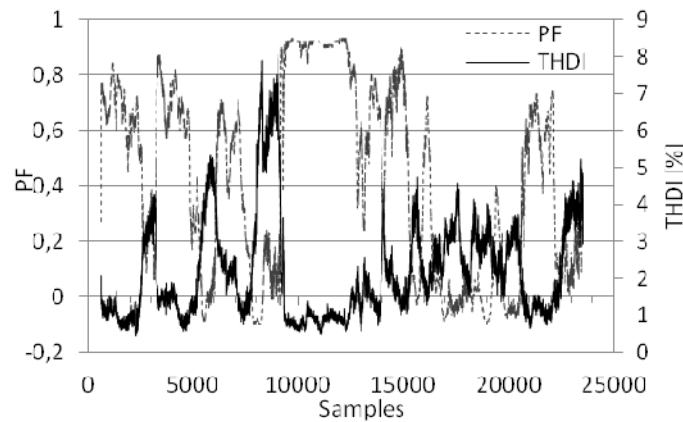


Fig. 14. Variation of power factor during the monitoring period

The minimum registered value is 0.19 for the monitoring period when the wind farm is supplied from the mains supply. The condition that power factor is between 0.95 lag and 0.95 lead must be fulfilled only if the generated power is between 10% and 15% of wind farm rated power.

### 4. Conclusions

The integration of renewable sources within the existing power system affects its traditional principles of operation. The utilization of these alternative sources presents advantages and disadvantages. The existing trend of installing distributed electric power sources implies the establishment of an accurate study of their impact on power system operation and power quality.

The wind farms, connected to the power system through power electronic converters, can pollute the electrical network with harmonic components that must not exceed the stipulated limits. Harmonic index correlated with the generating power is proposed and monitored for the wind farms. In fact, the monitoring period characterized by low generated power and small amplitude currents, but highly perturbed, reveals the low power factor. During night operation of the wind farm (when the generated current is small) the *THDI* can reach 80% value. During day operation of the wind farm (when the generated current is large) the *THDI* reaches 2% value. These values have small relevance from practical point of view.

The present paper proposes a distortion factor *TGDI* that more clearly illustrates the relationship between the RMS electrical current and the distortion level. The proposed indicator *TGDI* is introduced for assessing the operation of wind farms in terms of injected harmonics. The indicator *TGDI* can better define the effect of harmonics into the power grid, taking into account the variation corresponding to the power injected into the network.

The proposed index represents a parameter that can qualify the wind generators in term of harmonic disturbances giving a tool of comparison between different wind turbines and converters submitted for the installation.

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