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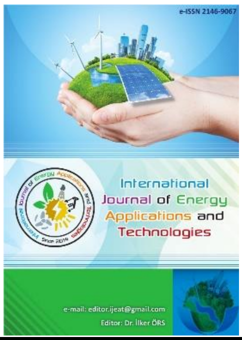


Original Research Article

# Harmonic analysis of a wind energy conversion system with small-scale wind turbine

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## ABSTRACT

Small-scale wind turbines, which have nominal power capacity less than 50 kW, are generally used in residential and agricultural applications. These turbines are simple-constructed structures, so they are not fully equipped with power quality controllers as bigger ones. Therefore, wind speed and direction affect output voltage and thus battery charging performance directly. It is necessary to determine the generating characteristics of these types of turbines in detail for appropriate output. According to this necessity, in this study, output voltage of an actual horizontal axis wind turbine is analyzed by using the measured data. Harmonic distortion levels for various frequencies are determined from such values. These results are discussed and possible solutions are offered for a quality energy generation.

*Keywords:* Harmonic analysis, Power quality, Wind turbine, Renewable energy, Distributed generation

## 1. Introduction

An increasing number of countries are using wind power for daily applications such as water pumping systems. Wind power is preferred as an alternative energy source because it requires no fuel and generates no greenhouse gas emissions [1]. Wind turbine studies are observed widely in literature. There are studies on design [2-5], analysis [6-8] and control [9, 10] of wind turbines. In addition, researchers are studied the types of turbines, horizontal axis [11, 12] and vertical axis [13, 14].

A typical large-scale wind turbine has a rotor diameter ranging from 50 m to 100 m. It produces power between 1-3 MW. When compared to large-scale wind turbines, small-scale wind turbines (SSWTs) have rotor diameter ranging from 3 m to 10 m and having a power generating capacity of 1.4–20 kW [15]. SSWTs can operate at low wind speed, generate minimal noise and there are no known safety hazards. In spite of several advantages, very few small-scale wind turbine models have been developed [16]. On the other hand, for a proper design and analysis, wind has to be modelled very carefully, which can be so-called fuel of wind turbines. As it is not possible to determine and model the absolute character of wind, working on actual systems become vital for a detailed analysis.

In this study, a horizontal axis wind turbine that physically installed at Bitlis Eren University Rahva Campus is analyzed. Output voltage value of the system is measured by using the Fluke 435 II Power Quality and Energy Analyzer. Such device can measure and save the all operational data of a system. Saved harmonic data is investigated and results are discussed in terms of power quality, effects of harmonics on charging performance and possible solutions for such systems.

## 2. Mathematical Model of Wind Power

Mathematically modelling of wind power can be given as follows [17-19]:

$$P_m = \frac{1}{2}\rho A V^3 C_p(\lambda,\beta) \quad (1)$$

In this equation, ρ is air density (kg/m$^3$), *A* is swept area (m$^2$), *V* is wind speed (m/s), $C_p$ is power transform coefficient, λ tip-speed ratio and β is the pitch angle, which is the angle between the plane of rotation and blade in terms of radians. In this study, β has a constant value of 0$^o$ to obtain maximum $C_p$ value. $C_p$ coefficient can be calculated as;

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \quad (2)$$

The c coefficients in equation 2 have average values of $c_1$ = 0.5176, $c_2$ = 116, $c_3$ = 0.4, $c_4$ = 5, $c_5$ = 21 and $c_6$ = 0.0068. Other parameters are;

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0,08\beta} - \frac{0,035}{\beta^3+1} \text{ and } \lambda = \frac{\omega r}{V} \quad (3)$$

where ω is turbine rotor speed (rad/s) and r is radius of the turbine blade in meters. As swept area is defined;

$$A = \pi r^2 \quad (4)$$

Finally, obtainable torque can be formed as;

$$T_m = \frac{1}{2\omega}\rho\pi r^5 C_p(\beta,\lambda)V^3 \quad (5)$$

The Eq. 5 is the net power that can be obtained from wind turbine. However, especially wind speed is in nonlinear character. In large-scale wind turbines, effects of this nonlinearity on output voltage can be eliminated by developed control systems, which is expensive and complex to be used for small-scale turbines.

## 3. Harmonic Distortion

Voltage and current waveforms that supplied from any source are desired to be pure sinusoidal. This is a vital necessity for stability and reliable operating of devices. Nonlinear loads in energy systems or insufficient power generation causes production of harmonics. Harmonics causes extra losses in motors, generators, capacitors, transformers and energy transmission lines. In some cases, harmonics cause the power system components to be damaged or disabled. In addition, harmonics would increase the occurrence of resonance. Over-currents and voltages that may occur because of resonance would cause great damages on system devices. These unwanted waveform distortions have to be detected and eliminated as soon as possible for protecting systems. Harmonics are eliminated by using filters. Three types of filters are being used for harmonic elimination. These are passive, active and hybrid filters. Passive filters are consist of passive circuit elements like capacitor and inductor, and one branch has to be used for each harmonic level, where active filters are more developed structures that includes a power supply, detects and eliminate both harmonics and interharmonics more efficiently. As a significant disadvantage, passive filters would cause resonance by interacting various network elements. The most common type of passive filters is the parallel or the shunt passive filter. Shunt passive filters are widely used to mitigate one or more harmonic frequencies. Their simple construction, reliable operation, and costs have made them one of the most frequently applied solution for power factor correction and harmonic mitigation in industrial applications [20, 21]. Another type of passive filter is the series filter. It is connected series to eliminate the harmonics.

Active filters can be connected in parallel or in series with the load. Active filters are used in high-frequency applications especially in communications, digital signal processing circuits and medical electronics [22]. The greatest challenge of designing active filters is the optimum selection of the passive elements [23].

As the principal operating idea, active harmonic filters inject current that is opposite in phase with the harmonics of the fundamental current. This is the way to eliminate the harmonic components from the fundamental current [24]. As another type of harmonic filter, which is called hybrid filter, that combination of active and passive harmonic filters, is being used widely nowadays. There are different kinds of hybrid filters, which all try to achieve a high performance in the elimination of harmonics while minimizing the installation costs and power losses [25]. Fig. 1 shows configuration of the hybrid filter.

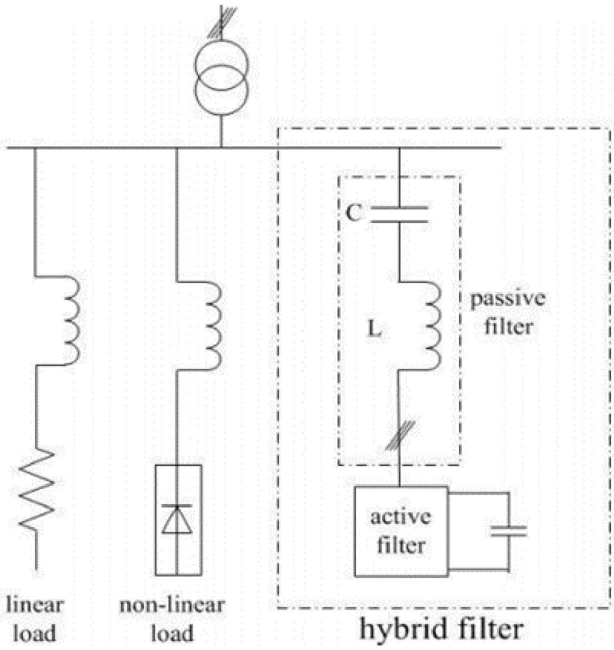


**Figure 1.** Hybrid harmonic filter [25]

Harmonic analysis is being widely studied in literature, in terms of passive filter solutions [26, 27], active filter solutions [28, 29], and effects of harmonics on systems.

Total Harmonic Distortion (THD) is the sum of all harmonic levels of current or voltage compared to the fundamental frequency. Harmonic distortion is happened by the injection of waveforms that are multiplied frequencies of fundamental. THD for voltage and current are calculated as follows respectively,

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \quad (6)$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \quad (7)$$

In these equations, $V_1$ is the voltage of fundamental frequency, $V_n$ is the voltage of n$^{th}$ harmonic, $I_1$ is the current of fundamental frequency and $I_n$ is the current of n$^{th}$ harmonic.

## 4. Analysis of System

According to the aim of this study, output data of the wind turbine that installed at Bitlis Eren University Rahva Campus, which is given in Fig. 2, is collected and analyzed. Properties of the wind turbine generator is shown in Fig. 3.

**Figure 2.** Wind turbine

As shown in Fig. 3, turbine has a generator that generates three-phase 24 V AC (line-to-line) voltage value at a rated wind speed of 12 m/s. Turbine output data is collected for analysis. Fluke 435 II Power Quality and Energy Analyzer is used for measurement.

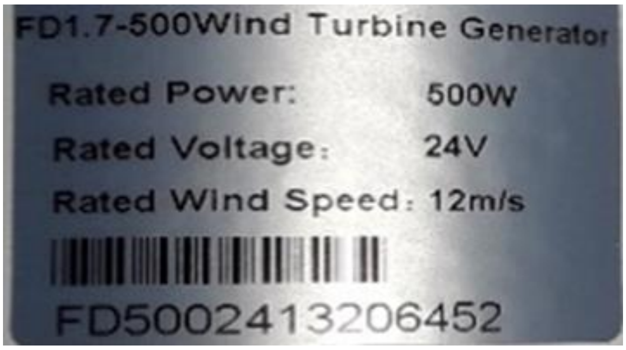


**Figure 3.** Wind turbine generator parameters

## 5. Results and Discussion

The harmonic levels at the output of the small-scale wind turbine are measured by the Fluke 435 II Power Quality and Energy Analyzer that given in Fig. 4 which has ability to measure harmonic orders from 1 to 50 of harmonic groups according to IEC 61000-4-7. Harmonic levels for each phase of generator are given in Fig. 5.

**Figure 4.** Fluke 435-II power quality and energy analyzer

In Fig. 5, vertical axes refer the harmonic levels in percentage of main component of sinusoidal waveform. Horizontal axis refers the harmonic order. Average values for each harmonic that obtained during measurement is summarized in Table 1. Proposed values are percentages that compared with main harmonic. Because of the generator structure, each phase has almost same harmonic generation characteristic. The asymmetrical waveforms may contain DC components and even ordered harmonics. In this study, according to measured data, even number harmonics have very low values that can be tolerated, so they were not taken into account.

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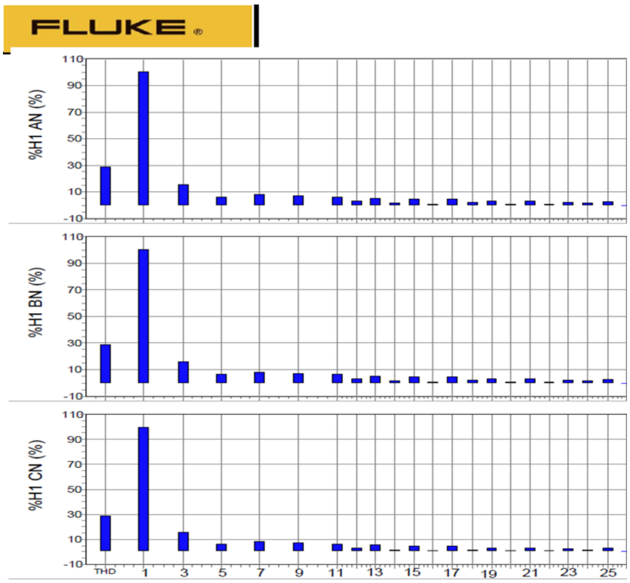


**Figure 5.** Harmonic levels for each phase

**Table 1.** Harmonic values

| Harmonic Order | Average Harmonic Value (%) |
|---|---|
| 3 | 15.746 |
| 5 | 6.218 |
| 7 | 8.048 |
| 9 | 7.1 |
| 11 | 6.374 |
| 13 | 5.312 |
| 15 | 4.721 |
| 17 | 4.503 |
| 19 | 3.151 |
| 21 | 3.165 |
| 23 | 2.044 |
| 25 | 2.601 |

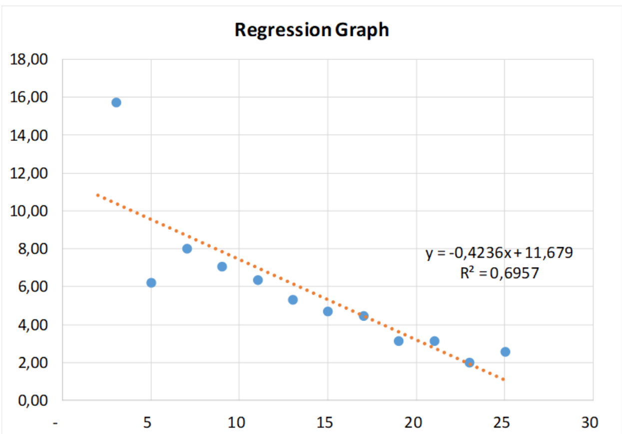


**Figure 6.** Regression graph

In Table 1, harmonic levels up to 25th order were given because referring to Fig. 5, harmonic levels were observed decreasing and have tolerable values after 25th order. It is clear from Fig. 5 that, harmonic level decreases by increment in harmonic order. This can also obtain from Fourier analysis.

A total harmonic distortion (THD) level of voltage has a value of 28.56 %. According to the EPDK (Republic of Turkey, Energy Market Regulatory) standards, $THD_V$ should be below 3%, where $THD_I$ should be below 8% [30]. It is clear from measurements that, system has a very high level of $THD_V$ and would cause serious damages on devices. For a clear understanding, also, regression analysis is performed between the harmonic order and average harmonic value, and results are summarized by graph given in Fig. 6.

Wind turbine is charging the batteries via a charger unit. This charger is shown in Fig.7.


**Figure 7.** Charge controller

The charge controller has DC output to charge the batteries. According to the distorted AC voltage waveform that generated by wind turbine, DC output of the charger is formed as given in Fig. 8 [31].

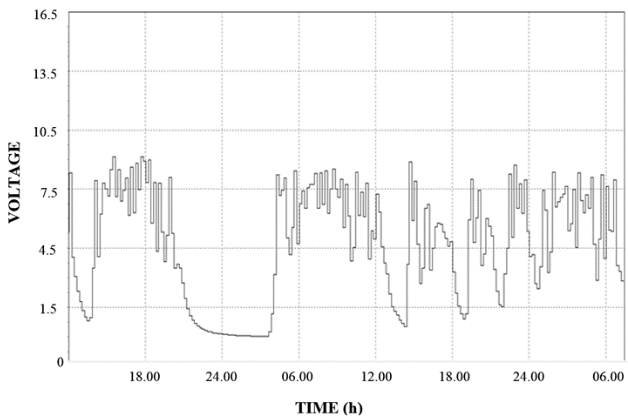


**Figure 8.** Charger DC output voltage

## 6. Conclusion

With the conventional energy sources, electrical energy generation by using distributed generators that consist of renewable energy sources as photovoltaic systems and wind energy systems are increasing rapidly worldwide. Besides the advantages of such systems, they have some disadvantages in terms of power quality. Especially energy generation by using wind via wind turbines, require more attention for a quality output because of the nonlinear characteristic of wind. While it is more possible to take precautions for power quality issues at large-scale wind turbines, it is not appropriate in general for small-scale ones that designed for personal use. In this study, power quality issues that may be encountered in small-scale wind turbine are investigated. System is physically installed so obtained results are actual values that affected from all atmospheric effects. This allows researchers to obtain highly accurate data for more accurate analysis. Results show that there are serious harmonic generation because of the variable character of wind. It is clear that harmonic distortion affects charging performance directly. Therefore, harmonic distortion has to be minimized not only for power quality but also for stability of whole system. Researchers are in progress of eliminating the harmonics of these type wind turbines as a future work.

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