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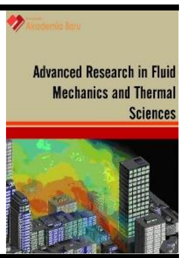

Investigation of Small Wind Turbine Noise as per IEC 61400-11 and AWEA 9.1 Standard

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ABSTRACT

This paper analyzes the noise generated from a 5 kW test wind turbine generator (WTG), having hub height, rotor diameter, cut-in and rated speed of 15m, 4m, 3 m/s and 12 m/s respectively, according to IEC 61400-11 (acoustic noise) standard. It discusses the realistic and comparable performances of small WTG that sets its own characteristics in terms of power and acoustic performances. Standard set by American Wind Energy Association (AWEA 2009) has also been incorporated in this research together with IEC 61400-11. For measuring noise level, the averaging period has been considered to be 10-second as per AWEA 2009. The study attempts to analyze time-series noise data recorded at different distance from the WTG for finding Noise (dB)-Frequency (Hz), RPM-Volt and Noise-RPM relationship. The current analysis done with the help of wind speed histogram bin each of size 1 m/s estimates that, the ranges of RPM, overall noise and background noise lie between 0 - 170, 45.17 (dB) - 48.78 (dB) and 33.2 (dB) - 65.6 (dB) respectively. The correlation between the WTG noise and background noise indicates for the research that the environmental impact due to noise for the WTG is subject to analyze and may not be underrated.

Keywords:
Small wind turbine; noise analysis; IEC 61400-11; AWEA 9.1; health impact

1. Introduction

Concentration of greenhouse gas is increasing due to increase in use of fossil fuels [1-3] causing the whole world to find alternative solution of energy sources. Wind energy being not a new idea or concept is such a kind of source which helps to build a sustainable energy solution by dint of the proper and systematics use of wind energy. For multifaceted energy application, wind has been used from the remote past of human civilization. Recent era has witnessed that, wind has become one of the core concerns of research in energy sector. Concerning about global climate change due to the emission of CO_2 from over-industrialization has been increased after the decisions taken from many of the global summits and conventions like Kyoto Protocol 1997, Paris Climate Convention in 2015

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etc. Generation of wind energy is thereby considered to have greener solution to mitigate the climate problem throughout the globe. Wind as proven to be one of the sources of an optimal power generation system can control CO_2 emissions by 828 g/kWh compared to coal power generation. As far as the wind energy is considered, the emission of pollutants such as CO_2 and CH_4 is 1/50 to 1/100 that of other energy sources, assuming that the wind speed is more than 8 m/s [4].

But the environmental and social issues caused by wind turbine generator (WTG) have also become prominent to work with. Noise defined as any "unwanted sound" [5] emitted from WTG is one of such issues regarding the sentiments of the general public. In the 1980s the first articles regarding noise annoyance from large wind turbines were published by Manning [6] and Hubbard *et al.,* [7]. A close vicinity of WTG in operation produces noise which may be a good reason of public annoyance [8]. Noise gives very indefinable impression to people in variable manners. Noise that may be soothing to one person may make another person crazy [9]. For WTG, noise may come from a number of sources like WTG aerodynamics and its mechanical equipment, though mechanical noise is not considered to be the dominant source of noise from wind turbines [10,11] at its first phase of life-cycle. The rotation of the rotor along with other parts are responsible of emitting mechanical noise, though this kind of noise impact significantly less when environment is concerned. Notable that the rotor of a WTG is connected to a generator that converts mechanical energy into electrical energy [12]. Noise generated for WTG aerodynamics is louder enough to be perceivable by the human ear within a certain decibel level, and the pressure range of noise at which it is heard is a dependent factor. Each wind turbine produces noise from its own character and level depends on many variables taken into account [13].

There is a dependent relationship wind speed and noise emitted by WTG - more the wind blows, more the WTG rotor rotates and more the energy is produced. And one thing is left - more the noise is emitted from WTG. The noise output of a wind turbine generator is universally determined from controlled site tests in accordance with international standard IEC 61400-11 "Wind turbine generator systems - Part 11: Acoustic noise measurement techniques" [14] though different noise emission regulations and standard for wind turbines exist on earth. For example, the German noise standard [15] allows for a sound level of 45 dB, whereas the Dutch noise regulation [16] adjust the allowed turbine limits depending on the wind speed. Again, the British assessment method [17] allows for 5 dB higher turbine sound level L_{Aeq} than the measured background sound levels $L_{A,90}$ at different wind speeds. There are four types of noise generated from a wind turbine in operation: (1) tonal noise which has a discrete frequency, (2) broadband noise which has a continuous frequency, (3) low frequency/infrasound noise e.g. noise below 200 Hz as Lowson [18] and Jhu et.al [19] describe are in fact predominant in the case of emitting noise from WTG generated from the interaction between environment and the turbine blades, and (4) impulsive noise. Notable that, broadband noise is caused by the interaction of boundary layer turbulence with the trailing edge of the turbine blades and is also described as a characteristic "swishing" or "whooshing" sound [20]. Aerodynamic noise is in fact a broadband type noise with having some low-frequency and tonal characteristics. A typical aerodynamic noise from a 2 MW turbine can reach up to the level of 99.2 dBA [21]. But for small WTG, which is the concern of this paper, will also be important to assess the noise frequency and magnitude level for the vicinity of habitats. WTG noise contains less low frequency compared to road traffic noise levels which are considered normal and acceptable [22], yet there are effects to be noted for the emitted noise.

Frequency as well as magnitude are the two major factors that help defining the characteristics of noise. The magnitude of noise can be well explained either in terms of noise power level indicating the acoustic power with which the noise is emitted from the source, and/or noise pressure level indicating the intensity of noise propagated experienced by the listener located at a given point [23].

Though to some extent, the noise propagated from the WTG is masked by the background noise created from trees, forests, buildings etc., the propagated WTG noise needs to be estimated. Masking wind turbine noise has been studied with natural ambient noise and noise from road traffic [24]. Ambient noise level usually increases faster than the WTG noise, thereby increasing the masking probability [25].

Focusing on small scale wind turbine with the capacity of 5 kW is only in the sense that, small wind turbines in generally are meant to be installed near residential areas adjacent to power loads, and much of relevant researches in this respect have been conducted [26,27], this research will investigate the noise generated from WTG through showing the correlation of some related variables like Wind speed, RPM, Volts etc. It will also investigate if the noise emitted from the experimented WTG is a kind of annoyance to the people according to the standard. The research is novel in the sense that it combines time-series noise measurement as per both of IEC 61400-11 standard and AWEA 2009 standard analysis that also tends to deal with environmental issues.

2. Theoretical Analysis of WTG Noise

Wind energy as it is known from the name itself is such a renewable energy source that does not cause environmental pollution, and its use is growing very fast around the world [28] with having been reported that the noise emitted from WTG may cause environmental pollution. The identification and perception of noise varies for different people. But it is well known that, the easiest way to identify the noise from WTG is to let to feel oneself 'how annoying' the noise exactly is, and there are a number of mathematical equations available for modeling the noise emission and propagation from wind turbines [29]. Sound intensity in physics is estimated in decibels and is calculated using the following formula

$$L_I = 10\,log(\frac{I}{I_0}) \tag{1}$$

where I is the measured sound intensity in W/m^2, I_0 is the limitary intensity of sound hearing. It can be expressed as in [30]

$$I = \frac{Power}{Area} = \frac{Energy}{Time*Area} \tag{2}$$

WTG noise data should be declared in accordance with IEC TS 61400-14 and will be defined as

$$L_{WD} = L_W + 1.645 \times \sigma \tag{3}$$

where L_{WD} and L_W are declared noise level and measured noise level respectively according to IEC 61400-11. σ is the standard deviation while measurement uncertainty are taken into account. The other computational method used for noise propagation over land when the noise pressure level L_P at a distance R from a wind turbine, radiating noise at an intensity of L_W is given by [31,32]

$$L_P = L_W - 10\,log_{10}(\,2\pi R^2) - \alpha R \tag{4}$$

where α is the sound absorption coefficient. For a given noise level of L_P, the sound power P_N expressed in W/m^2 can be approximated as

$$P_N = 10^{\left(\frac{Lp-90}{10}\right)} \quad (5)$$

The research considers the background noise level caused by wind while estimating noise level of small WTG. When the background noise and wind turbine noise are at the same magnitude, the wind turbine noise gets lost in the background [33]. Typical background sound levels range from 35 dBA (quiet) to 50 dBA for urban setting [34]. AWEA attempts to measure the turbine noise level from Eq. (6).

$$WTGNoiseLevel \quad = L_{AWEA} + 10\,log(\,4\pi 60^2) - 10\,log(\,4\pi R^2) \quad (6)$$

After that, once the background noise has been acquired, the overall noise level is measured from Eq. (7) [35,36].

$$OverallNoiseLevel \quad = 10\,log(\,10^{\frac{WTGNoiseLevel}{10}} + 10^{\frac{BackgroundNoiseLevel}{10}}) \quad (7)$$

Theoretically estimated noise level depends on the distance between WTG rotor hub to the noise sensor. There are different absorption coefficient values which are also important to consider to indicate that the impact of atmospheric absorption coefficient cannot be negligible to estimate noise level. In addition to it, it is also necessary to evaluate the fact that in any experimental environment, other noise sources are also available which too are needed to be estimated.

3. Experimental Study

In order to assess the noise from a WTG and to get detailed result, it requires time-series data for a number of operations in terms of maintaining different distances between the rotor hub and the noise sensor. The distance can be measured in a number of ways as suggested by IEC 61400-11. As shown in Figure 1, if hub height is *H*, and the rotor diameter is *D*, then the distance *X* of the position of sensor from the centre of the turbine base mathematically, according to the rule setup by IEC 61400-11, should be *X = H + r*, where r is the radius of the swept are, i.e. *D/2*.

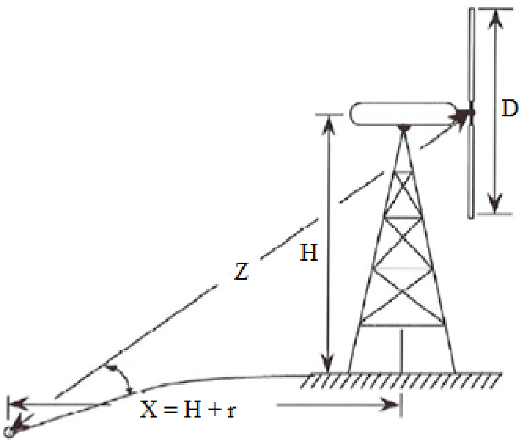

Fig. 1. Measurement scheme of noise through determining the distance between the sensor and the WT [37] (upwind direction)

Correct noise power level can be obtained through the estimation of the noise power from each sensor using the exact distances between the centre of the rotor and the sensor. Another approach is, to consider the distance to be measured from the centre of the rotor to the sensor, *Z*. It should be noted that, the noise of WTG needs to correlate with the wind speed measured at a specified or required height with the help of wind profile power lay shown in Eq. (8) where the reference height *z* must be utilized.

$$U_z = U_r \left(\frac{z}{z_r}\right)^{\varepsilon} \tag{8}$$

$$\varepsilon = \frac{ln(U_z)-ln(U_r)}{ln(Z)-ln(z_r)} \tag{9}$$

The standard measurement height of *z* is in generally accepted to be of 10 m. Practically WTG works in much higher altitude than standard measurement as wind speed increases with the increase in the height. Wind speed near the ground becomes lower and more turbulent due to many obstacles like forest, building, hills, vegetation etc. So it is impractical to commercialize WTG at lower level. That's why it needs to interpolate the wind speed at the reference height *z* to a specific height as per some international standards with the help of mathematical equations like power law profile given in Eq. (8) and (9). More the wind speed is, more is the RPM, and thereby more power is generated from the wind. Eq. (10) represents the power of the wind flowing into the wind turbine rotor [38].

$$P = \frac{1}{2}\rho A V^3 \tag{10}$$

Eq. (11) is the mechanical power output generated by the rotation of the wind turbine rotor.

$$P = T\omega \tag{11}$$

In order to understand the efficiency of the turbine it needs to calculate the coefficient of power, C_p, which is actually the ratio of the power generated by the WTG to the wind power specified by the manufacturer of the WTG. C_p can be conceived as a concept of aerodynamic energy conversion efficiency index. A WTG can never produce the power as specified by the manufacturer. Theoretically, the maximum value of the power coefficient is 0.593 for a horizontal axis wind turbine. This maximum value is known as Betz limit. The Betz limit is derived from actuator disk momentum theory and is the theoretical maximum assuming that the flow is steady-state, in viscid, and irrotational [39]. Normally noise propagation methods use general simplified meteorological assumptions, e.g. constant downwind measures, temperature inversion etc. This research has been conducted on the experiment for the analysis of WT generated noise and influence of background noise with a turbine capacity of 5 kW. The current wind turbine profile used for the research indicates the frequency and volt relationship as 1 Hz equals to 6.2 volt the WT generates. The calculated Hz then will be used to find RPM of the turbine as 1 Hz equals to 4 RPM. Different wind speed was considered to measure the noise with TES 53H noise sensor which is tested and validated for wind turbine noise calculations. For the ease of analysis and to estimate the noise level, two procedures in the research are possible - measurements and predictions, though in terms of noise analysis, predictions are considered acceptable it gives a reasonable accuracy. AWEA defines a number of rated noise level like 40 dBA, 45 dBA, 50 dBA, 55 dBA, all those can sum up from the derivations of the values of WTG Noise Level and Overall Noise Level from Eq. (6) and (7) in order to derive graphs shown in Figure 2 and Figure 3 respectively.

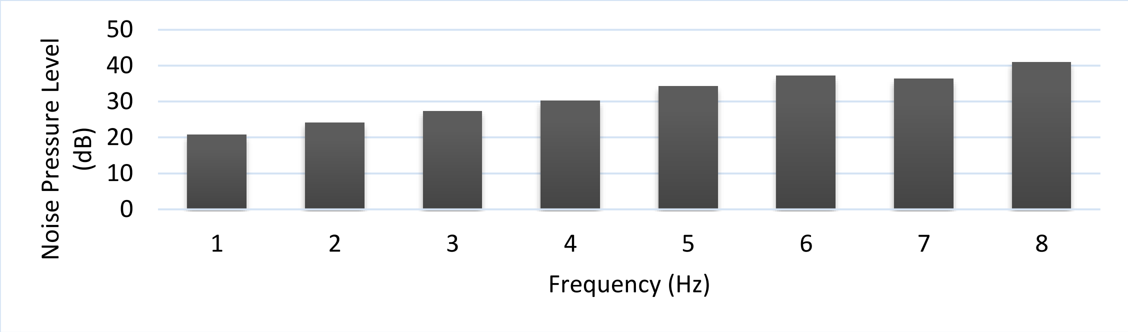

Fig. 2. WT generated acoustic noise spectrum variation different frequency

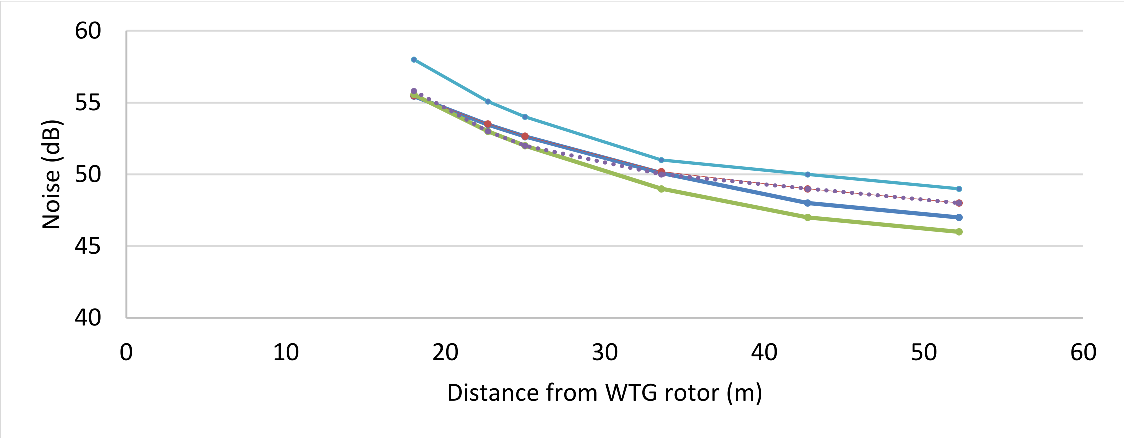

Fig. 3. Overall noise level for AWEA rated noise level of 45 dB at different distances (m) from the rotor centre of WTG

From the obtained experimental research, it may be observed that the noise level of WTG significantly depends on the background noise level. Table 1 presents wind speed at WTG height at reference conditions.

Table 1
Reference conditions

Hub height (m)	15						
Wind speed (m/s)	3	4	5	6	7	8	9

According to AWEA 9.1-2009 section 3.1 (more specifically sub-section 3.1.1 to 3.1.4), WTG noise levels must be measured in accordance with IEC 61400-11 ed.2. But it gives some additional guidance after which Table 2 is presented that displays the WTG noise level at different specified AWEA rated noise levels. AWEA 9.1-2009 specifies that the time-series noise data will be of 10-second averaged instead of 1-minute [34].

4. Results

4.1. Noise Distribution

Wind speed and direction have also been measured directly from the turbine height rather than to use power profile law, and method of bin has been employed to analyse the data as specified by AWEA 9.1-2009. Noise from different distance has been measured as per IEC 61400-11 as shown in Figure 1. Table 2 shows the WTG noise levels for different distances between WTG rotor hub and the noise measurement sensor. Ambient sound can be responsible to mask the sound from WTG. As a result, background noise levels are also to be considered as stated.

Table 2
WTG noise level at AWEA rated noise level of 40dB, 45dB, 50dB and 55dB

Distance, m (WTG Rotor Hub-Sensor)	40dB	45dB	50dB	55dB
18	50.44	55.44	60.44	65.44
23	48.45	53.45	58.45	63.45
25	47.60	52.60	57.60	62.60
34	45.05	50.05	55.05	60.05
43	42.95	47.95	52.95	57.95
52	41.21	46.21	51.21	56.21

It was determined that WTG generated noise level at different wind speed that, when the distance of the sensor from the WTG hub increases, the noise recorded from it becomes more close to the background noise level. The power curve shown in Figure 4 is a 5 kW wind turbine with maximum RPM of 200, cut-in speed of 3 m/s, rated wind speed 12 m/s, which can withstand the wind speed with the maximum value of 60 m/s. Figure 4 shows actual power produced at various wind speeds by the WTG with also showing the theoretical power in the wind as specified by the WTG manufacturer at these wind speeds.

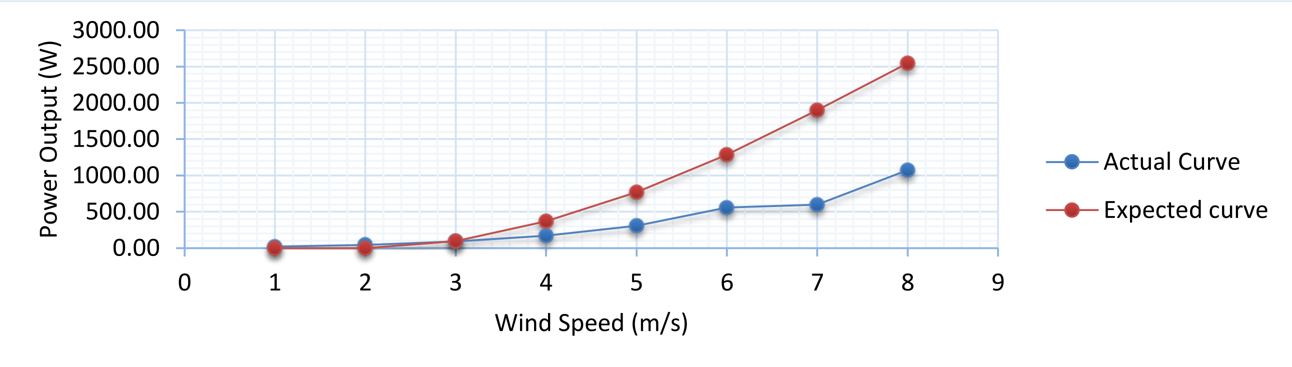

Fig. 4. Actual (experimental) and expected (WTG specification) power curves

4.2. Estimated Error

Table 3 and Figure 5 interpret the values of noise error. The estimated power error can be calculated from experimental findings and the manufacturer specification as identified in Figure 2.

Table 3
Error analysis for bin averaged experimental data

SN	RPM Range	Average RPM	Noise (dB)	Error (%)
1.	100-110	105	45.17	1.19
2.	110-120	115	45.93	1.51
3.	120-130	125	46.21	0.81
4.	130-140	135	47.03	1.26
5.	140-150	145	47.31	0.57
6.	150-160	156	47.64	-0.01
7.	160-170	165	48.02	-0.47
8.	170-180	174	48.36	-1.01
9.	180-190	182	48.78	-1.38

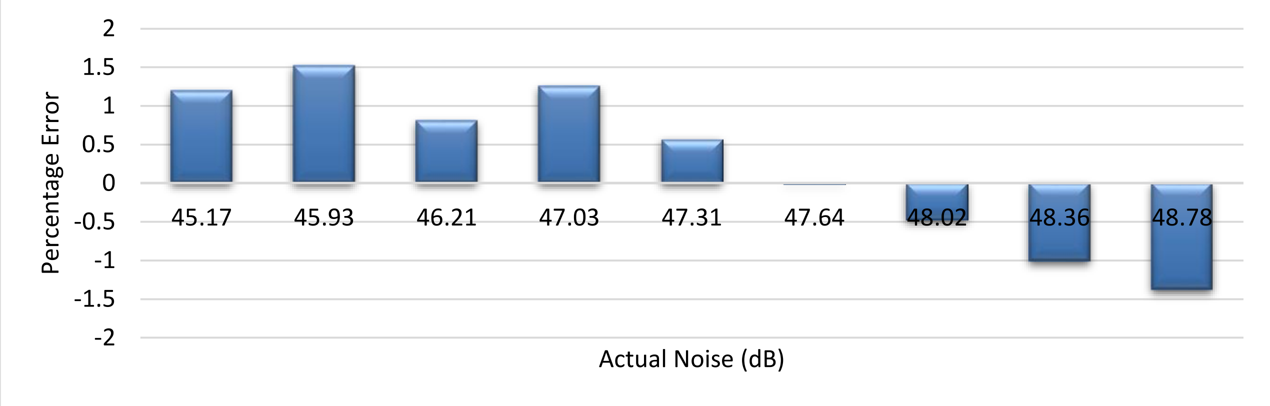

Fig. 5. Noise error from experimental data

The percentage power measurement error is of the wind turbine as specified by the manufacturer shown in Figure 6.

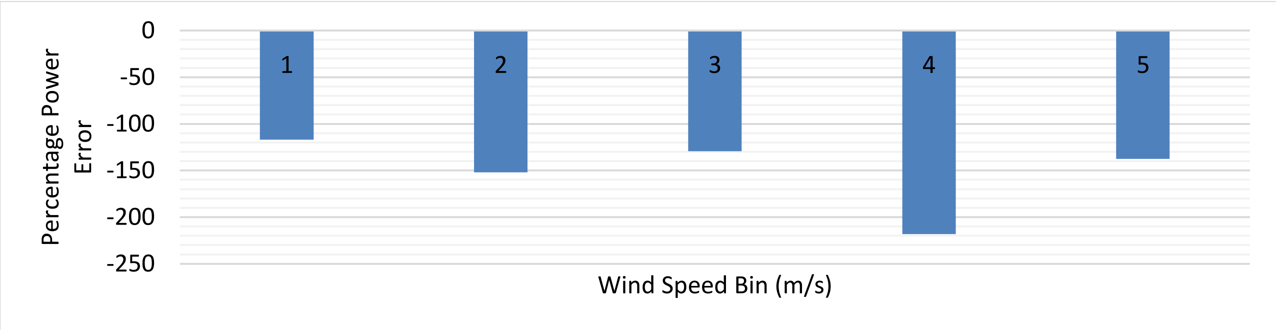

Fig. 6. Percentage error of power measurement according to WTG specification

The cut-in speed of the tested WTG is 3 m/s, and as it is being seen from the Table 3 above that, the power increases as the wind speed increases. The linear relationship of wind speed with RPM is also clear from the table. From 3 m/s as the rated speed, the power output starts generating electrical energy at a rotation speed of 91 RPM. In general, if higher wind speeds are available, the noise generated from the WTG is masked by the background noise. In order to test the performance of the WTG, a number distance was observed. The noise from each distance has been estimated as shown in Table 4.

Table 4
Overall noise level at different distances from WT

Hub Height (m)	WT base-Sensor Distance	Distance from Rotor centre (R)	Overall noise level at AWEA rated sound level (L_{AWEA}) of 40 dB				
15	10	18	50.48	50.57	50.82	51.5	53.24
	17	23	48.51	48.65	49.03	50.1	52.31
	20	25	47.68	47.84	48.3	49.5	51.98
	30	34	45.19	45.46	46.23	48	51.21
Background noise level (dB)			30	35	40	45	50
AWEA rated noise level (dB)			40	45	50	55	

Though, this is a fact that WTG noise may not be heard on the condition that the WTG is emitting a noise at 10 dB lower than the background noise. Coefficient of power declines significantly as the wind speed increases and so does RPM both of which are shown in Table 5.

Table 5
Power output and power coefficient according to wind speed

Wind Speed (m/s)	RPM	Power Output (W)	C_p	Comments
1	82.93	21.71		Before reaching to cut-in speed (3 m/s), WTG produces zero power output.
2	96.50	41.78		
3	109.21	91.38		
4	120.67	169.02	0.46	
5	136.94	306.00	0.40	
6	148.50	559.72	0.44	
7	149.22	597.74	0.31	
8	163.89	1072.25	0.42	

It can be understood from Figure 2 that, the coefficient of power minimizes to 31% during the production of power of the WTG at the wind speed of 7 m/s. In that context, the tested WTG gives a satisfactory output. From the analysis, the power estimation has been done as shown in Figure 7 and RMP-Noise relationship from the actual experimental values as shown in Figure 8.

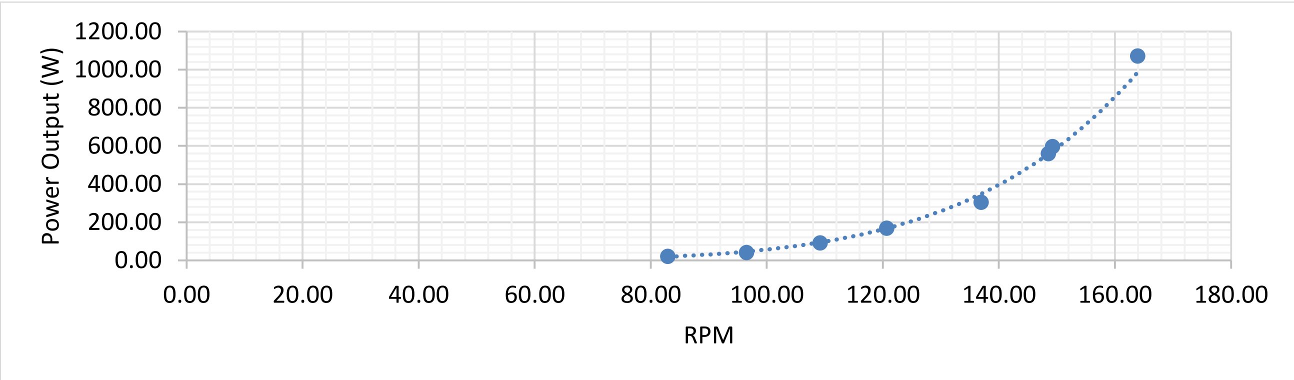

Fig. 7. Power output according to RPM

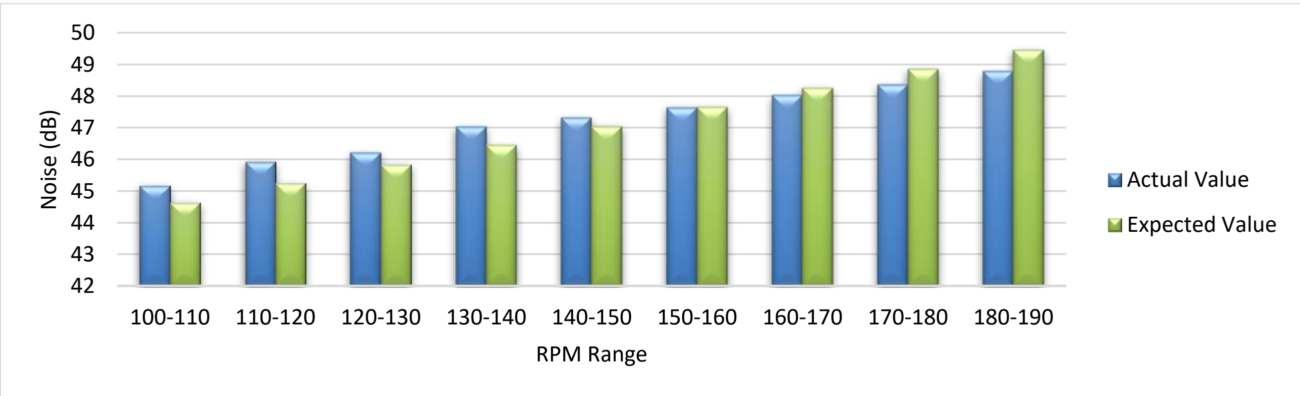

Fig. 8. Noise-RPM relationship for expected value and actual experimental data (bin averaged)

It will be worth to note here that, the most important property of a wind turbine is its power coefficient (Cp) that measures the actual power output generated by the turbine [40]. In general point of view, good quality wind turbines fall in the 35-45% range of the power coefficient level.

4.3 Health Impacts of Noise Exposure

This section will analyse the possibility of health hazards that may incur from the noise emitted from the turbine. Various research indicates that, exposure to extremely high noise levels can also cause headaches, irritability, fatigue, constricted arteries, and a weakened immune system [41]. A study conducted in Europe, incorporating sixteen sites from Denmark, Germany and Netherlands showed that only 6.4 per cent of the residents felt that the noise from wind turbines as annoying [42]. Perceptivity of the noise as per the rate of its increase is shown in Table 6.

Table 6
Perception of noise due to its rate of increase

Increase of noise (dB)	1	3	6	10
Level of perception	Insignificant	Just perceptible	Clearly perceptible	Drastically perceptible

This research indicates that, due to the increase in distance between the WTG tower and the sensor, the noise intensity reduces significantly which is beyond the harmful level of human ear and other sensitive units of human body. Although the limit varies from country to country, most of the countries have strict regulations on the levels of noise emissions permissible in residential localities [43]. For example, the highest permissible noise level from wind turbines in some countries can be shown in Table 7 which are thought of as proven to be safe for human health. It is to be noted that this increment is not all about the health hazard caused by noise emitted from WTG.

Table 7
Tolerable limits of wind turbine noise by countries

Countries	Maximum tolerable noise (dB)			Remarks
	Day-time	Night-time	Sensitive area	
Sweden	40		Not Specified	
USA	Not Specified	50		Oregon Department of Energy
Denmark	45		40	Special government legislation for wind turbine in residential area.
Germany	50	40	Not Specified	Residential area
Netherlands	50	40	Not Specified	Permitted noise vary with wind speed

Sounds lower than 16 Hz are infrasound whereas higher than 20 kHz is known as ultrasound [44,45] which human hearing does not perceive, and which are not a subject matter of this research. Higher levels of infrasound and ultrasound evoke a feeling of discomfort, and cause harm to human health [46,47]. However, this experiment reveals that, as the distance between the WTG rotor and the noise sensor increases, the captured noise become more close to the background noise as shown in Table 6 [48]. This means, with the increment of the distance, WTG emitted noise insignificantly influence the total noise level. The inverse linear relationship between the noise intensity and distance with rather invoke more background noise that helps initiating the masking of the WTG noise.

Research indicates that the sound levels of noise, which are higher than 140 dB, evoke pain and may injure hearing organs [49,50]. In the current research on small WTG, the measured noise ranges between 45.17 dB to 48.78 dB which is not responsible for any kind of health issue like this. Health impact due to acoustic pollution form the emitted noise of small WTG which usually is used for standalone power source application in residential places or other selected areas can thus be easily formulated.

5. Conclusions

This research was conducted with a test WTG having a hub height of 15 m along with a 4 m of rotor diameter, a total distance of 17 m between the sensor and the centre of the base of WT has been ensured as per both IEC 61400-11 and AWEA 9.1- 2009 standard. The following are the summation of the current research

i. International recognized standards ensued in this research suggest to collect data with varying distances for the understanding of the noise.
ii. A total of four different distances between rotor hub and the sensor have been ensured to measure noise data.
iii. Noise data have been analysed as per AWEA rated noise level defined as 40 dBA, 45 dBA, 50 dBA, 55 dBA. WTG noise level for all the defined rated levels has been measured in this research.
iv. Overall noise level has been measured with the aid of AWEA rated background noise.
v. Noise intensity which is a function of wind speed in terms of when WTG noise is analyzed has been experimented in this research with the aid of AWEA rated background noise level.
vi. It was determined that WTG generated noise level at different wind speed that, when the distance of the noise sensor from the center of WTG hub increases, the noise recorded from it becomes more close to the background noise level.

The points outlined above identify that the influence of WT noise on the environment could not be underrated for WTG generated noise level calculation as in this research is corresponding to experimental measurements under natural conditions. The experimental study was accomplished at different distances from the wind turbine hence it may have a very good scope which might be applied for the understanding of noise pollution when wind turbine will be set up for power generation.

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