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ORIGINAL ARTICLE

Airborne Noise Emission Characteristics of Wind Turbines in Iran

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ABSTRACT

Wind-turbine noise emission and its environmental impact are considerable issues nowadays. The purpose of this study was to identify the sound emission pattern and sound characteristics of wind turbines on the largest wind farm of Iran. In order to prepare the daytime sound level (Ld) noise map, environmental noise measurement was done based on measuring $LAeq_{10\ min}$ three times a day according to the ISO9612 method. On the basis of IEC 61400-11.2006, sound characteristics and wind speed were measured simultaneously at the back and front of the wind turbines using TES-1358 Sound Level Meter and vane anemometer. Finally, data were analyzed using SPSS 16. The average daytime sound level (Ld) of wind farm was 63dBA which is 3 dB higher than the recommended level. Wind speed had a significant non-linear relationship with wind turbines noise up to 17 m/s approximately ($P<0.001$). Frequency analysis showed that the wind turbine noise is more in the low frequencies (below 1000 Hz). The wind turbine's noise was affected by the power and blade length of wind turbines ($P<0.05$).Sound pressure levels(SPL) in frequencies lower than 250 Hz are equal at the back and front of the wind turbines, however in higher frequencies, it is averagely 2dBA more on the back of the turbines. The blades of Manjil wind turbines rotate with approximately maximum power at high wind speeds. Hence, aerodynamic noise is higher than recommendation level; wind turbines noise is also sensitive to structural characteristic, wind speed, fluctuation and low frequency.

KEYWORDS: *Wind turbine, Noise, Airborne emission, Wind farm*

INTRODUCTION

Noise emission of wind turbines and its environmental impacts are among the most important issues of recent researches in wind energy engineering field [1]. Wind farms are new sources of energy around the world and there are discussions about characteristics of wind turbines noises [2]. Some sources have categorized the sounds generated by wind turbines into Mechanical sounds and Aerodynamic sounds. While mechanical sounds are created by the interaction of turbine components, the aerodynamic sounds are produced by the flow of air over the blades. The mechanical sounds have been significantly reduced by recent improvements in wind turbines whereas the sound emission from wind turbines is dominated by aerodynamic sounds [1].

The noise generated by wind turbines is tonal, broadband, low frequency and impulsive and a result of the function of wind speed, turbine design, distance, ambient sound levels and various other factors [1]. As the noise emitted by wind turbines is low frequency, it has potentially negative impacts on human health and

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environment.

If the sound level increases, it will cause sleep disturbances, stress and anxiety [3]. A relationship between the turbine's low noise frequency and its offensive effect on quality of life, sleeping, and behavioral reactions is reported [4-6]. A significantly positive relationship between the noise disturbance and the low frequency of noise on farm wind resistances is reported earlier [7]. The noise emitted by the wind turbines has feedbacks including the stress-related diseases and low life efficiency in farm wind resistances [4].

According to WHO Europe Region guideline, the limit of sound level in an annual average night exposure should not exceed 40 (dBA) considered as the lowest observed adverse effect level in residential area [3]. The sound power level created by a turbine is in the range of 90-105 dBA; which is 50-60 dBA in distance of 40 meters and 35-45 dB (A) in distance of about 300 meters [8]. Turbine noise increases by wind speed [8].

Due to impacts of wind turbine's noise on health, different methods including prediction, identification and noise propagation models were chosen. However, noise measurement provides the possibility of wind turbine's noise recognition as well as source distribution analysis [9-10].

There are concerns about the low frequency sounds of wind turbines. Hence, it is important to identify and assess the level of noise emitted by the turbines which are close to the residential areas [11].

The present study has been conducted on the largest wind farm of Iran which is very close to the residential areas and has the maximum number of turbines in Iran. This study was carried out with two aims: 1) Noise map preparation to find the airborne noise emitted by wind farm turbines, 2) Wind turbine's noise measurement to evaluate the amounts of sound characteristics for three types of wind turbines (300, 550 and 660 kW).

MATERIALS AND METHODS

Study Area: This research has been carried out in the largest site of Iran wind Farm located in Manjil Town, northern Iran in 2015. Since the town has strong winds, it is appropriate for wind turbines installation. The wind farm has about 1,653,116 square meters area. There are totally 52 turbines in operation which are located with a specific distance from one another as shown in Figure 1. There were 15 of 300 kW turbines installed, 16 of 550- kw turbines and 21 of 660 kw turbines, with the blade length of 17, 18 and 23 meters and the turbines were about 40, 45, 50 meter high [12].

Air pressure variations due to the geographical location of nearby mountains and Manjil Dam reservoir would cause day and night wind speed variation. Since the turbines are rotated, the blades have low resistance against rotation speed, Thus they should be stopped automatically in high winds. Due to the high speed winds in spring, data collection has been done in spring. Due to the high speed winds in spring, data collection has been done in spring. Whereas wind direction is frequently from northeastern to southwestern at daytime in summer and spring, it inverts frequently during the autumn and winter. Fig.1 shows the plan of wind farm and the location of wind turbines.

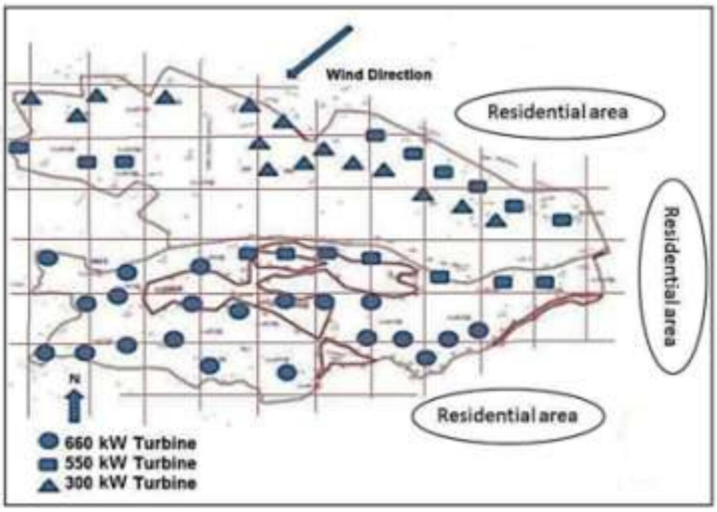

Fig.1. Location of wind turbines and measurement points

Data Collection: Data collection has been done in two phases during the spring season:

1) Environmental noise measurement
2) Wind turbines noise measurement

Phase 1: Environmental noise measurement

In this phase, the lattice method was implemented for environmental noise measurement [13]. Since the site of wind farm had a large area, it was divided into 200×200 m red grids (Fig.1). Overall, 40 stations were identified on the wind farm for measurement and according to ISO 9612; the centers of each grid have been set as the measurement points. The sound level meter microphone was set up at 1.5 m above the ground level and it was protected with a 9 cm foam wind shield [14]. In order to cover all the turbines, measurements have been made at the center of 40 points by TES-1358 sound level meter made by Taiwan. The sound level meter was calibrated 94 dBA at 1000 Hz with calibrator. The geographic locations of the points were specified using GPS. A and C-weighted filters which have been selected for noise level measurements. Wind speed rate in three time intervals 7 to 11 am, 11 to 4 pm and from 4 to 10 pm was almost monotonous, so the measurement of sound characteristics was measured three times a day: morning, afternoon and evening. Daytime sound level (L_d) was calculated by the use of the following Equation (1), where $LAeq_{10min}$ represents the "A" weighted average of equivalent sound level over a 10 minute period.

$$Ld{:}10\log\,[\tfrac{1}{T}\sum[ti_m\,10^{0.1(\text{Leq m})}+ti_a 10^{0.1(\text{Leq a})}+ti_e 10^{0.1(\text{Leq e})}] \qquad \textit{(Equation 1)}$$

Where;

L_d : A weighted Leq for daytime period (7 am to 10 pm)
T: daytime period (7 am to 10 pm)
Ti_m: exposure time in the morning (7 am to 11)
Leq_m: average of equivalent sound pressure level ($LAeq_{10min}$) in the morning
Ti_a: exposure time in the afternoon (11 am to 4 pm)
Leq_a: average of equivalent sound pressure level ($LAeq_{10min}$) in the afternoon
Ti_e: exposure time in the evening (4 pm to 10 pm)
Leq_e: average of equivalent sound pressure level ($LAeq_{10min}$) in the evening

Then the daytime equivalent sound levels of the measurement points have been used to draw noise map using SURFER 11 software.

Phase 2: Wind turbines noise measurement

Three turbines of each kind (300, 550 and 660 kw) have been selected randomly for noise measurement. This phase has been implemented on the basis of IEC 61400-11 Standard: 2012 requirements [15] and EPA guidelines 2003 [16]. As shown in Fig.2 and Table 1, the measurement points in front and on the back of the turbines were located in the distance of H+D/2, where H_{is} height of turbine (m) D rotor diameter (m). The microphone was mounted at 1.5 meters above ground level and it fitted with a one-layer windscreen.

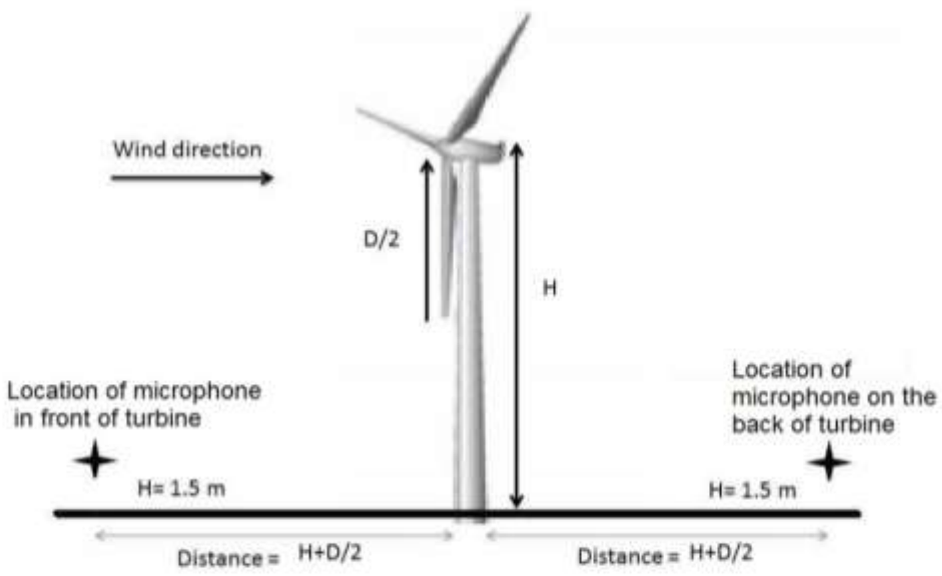

Fig.2. Location of measurement points in front and on the back of the wind turbines

Table 1. Distance of measurement location from turbine according to Turbines' characteristics

Turbine type (kW)	Blade's length (m)	Height of turbine (m)	Distance of measurement point from turbine (m)
300	17	40	57
550	18	45	63
660	23	50	73

According to Environmental Protection Agency, sound characteristics including $LAeq_{10\ min}$, C-weighted one-octave-band noise level, minimum and maximum of sound pressure levels and daytime average sound level (Ld) were measured by TES-1358 Sound Level Meter [17].

Because of non-monotonic sound caused by the rotating turbine blades, we added Signal-to-noise ratio (SNR) in our measurements. Signal-to-noise ratio (SNR) was calculated by different of L_{max} and L_{min}.

The measurement was done three times a day: morning, afternoon and evening at the mentioned points. In order to increase the accuracy, measurement of the sound characteristics was repeated three times in each time and the average was calculated for whole of sound characteristics. Then daytime average sound level (Ld) was calculated by Equation 1. Sound characteristics of each turbine were measured in different wind speeds (3 m/s to 25 m/s).

Wind speed measurements were done concurrently by Air Flow Edra 6 vane anemometer in the height of 10 meters of the wind turbines. In order to do the statistical analysis to confirm the results , normal distribution of each of the variables was initially tested using Kolmogorov-Smirnov test (KS-test) with a margin of error greater than 0.05.

After ensuring the normal distribution of the data, Least Significant Difference (LSD), bivariate correlation test, one-way ANOVA test and paired t-test were used to analyze the quantitative and qualitative collected data using SPSS16.

RESULTS

The results are presented in two parts, the environmental noise measurement and analysis of wind turbines noise measurement.

Environmental noise: Wind turbines distribute specifically on the wind farm. When wind blows, the wind turbines automatically turn to face the wind direction and the blades start rotating which produces noise. The pattern of noise propagation is shown in Fig.3. The map of isosonic curves is drawn up which represents the daytime sound pressure level (Ld).

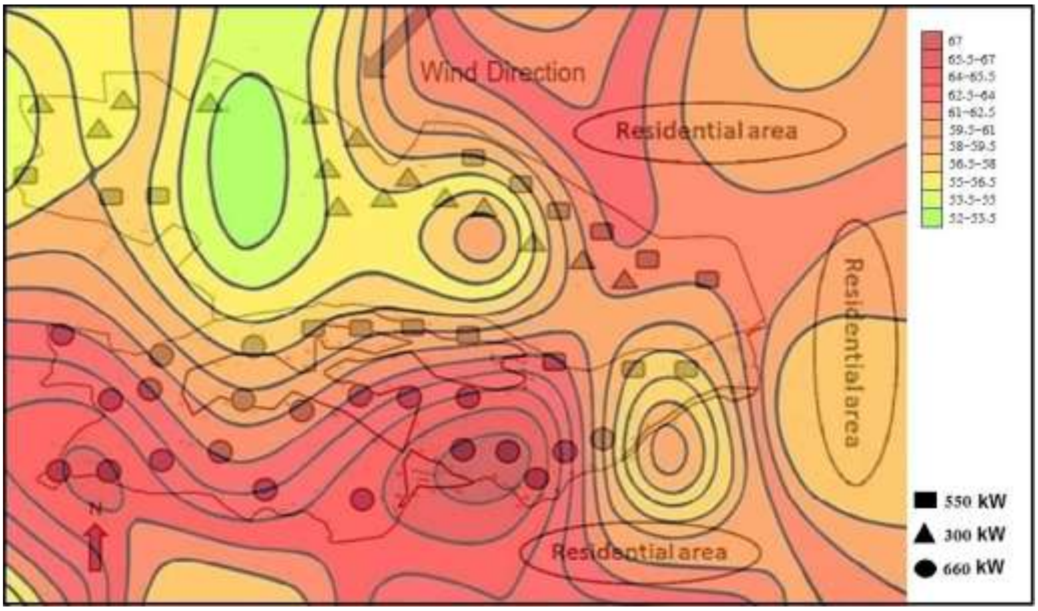

Fig.3. Noise map of Manjil wind farm according to daytime sound pressure level (dBA)

As shown in Figure 3, daytime sound pressure level (L_d) is higher in the areas where the 660 kw turbines were located (about 60 to 67 dBA). L_d is about 55 to 60 dBA close to 550 kW turbines and lower in the location of 300 kW turbines (about less than 55 dBA).

There are three peaks of L_d in the south of the noise map and one peak of L_d in the northern part. It shows the density of turbines is higher in this part that led to increase noise level. The approximate sound levels in residential areas are also shown in noise map (Figure 3). The noise

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exposure in residential areas placed on the southern part of the wind farm is more than that in the other areas and it is between the ranges of 58-65 dB. Since the wind direction affects propagation of the wind turbines noise, there is higher noise exposure in the southern residential area. There are lower exposure levels for people who live in the eastern parts of the wind farm. It is important where the larger turbines are located (southern part) the wind speed is averagely more than it at the other parts Statistical analysis showed that there is a significant correlation between the wind speed and sound pressure level directionally (*P<0.05*).

Wind turbines noise: The results of Kolmogorov-Smirnov test showed that all quantity variables (sound pressure level at one-octave-band central frequencies, wind speed, $LAeq_{10min}$, L_{max} and, L_{min}) follow normal distribution (P>0.05). Since all quantity variables follow normal distribution, the results of one way ANOVA statistical analysis showed a significant difference between the means of most of quantity variables in the morning, noon and evening groups.

Least Significant Difference (LSD) test showed that $LAeq_{10min}$ means don't have significant difference in morning and noon, while in morning and evening means have significant differences (P<0.001), so $LAeq_{10min}$ mean was 15dBA higher in the evening. Table (2) includes the daytime average sound levels (L_d) of different types of turbines. The noise measured in front and on the back of turbines had different characteristics including: day time sound level (Ld),10 min equivalent sound-pressure level ($Laeq_{10min}$), Signal-to-noise ratio (SNR) was calculated by different of L_{max} and L_{min} as shown in the Table 2. Regarding the non-monotonic sound caused by the rotating turbine blades due to the fluctuations of the rotational period blades, the signal to noise ratio has been calculated. Table 2 shows the sound characteristics and wind speed in front and on the back of the wind turbines.

Table 2. Means of sound characteristics of turbines and natural wind speed

Turbine type (kW)	Ld (dBA)	Measurement location	Descriptive statistics	Signal-to-noise ratio (dBA)	**$LAeq_{10min}$ [dBA]**					**Wind speed [m/s] in**		
								P-value of				
					Morning	Noon	evening	Paired t- test (*P*-value)	ANOVA	Morning	Noon	evening
300	60.6	forward	Mean	25.0	55.6	62.3	66.5	<0.05	<0.05	5.0	7.30	20.6
			SD	-	5.9	2.5	1.48			1.0	0.58	3.6
		backward	Mean	24.3	57.1	63.1	67.5			5.5	8.30	20.9
			SD	-	5.4	2.8	2.0			0.8	1.20	2.6
550	61.7	forward	Mean	23.3	64.6	61.3	67.5	=0.31		9.3	6.00	22.0
			SD	-	6.5	5.8	1.9			2.8	2.00	1.0
		backward	Mean	24.0	63.7	62.7	68.2			9.7	7.30	22.3
			SD	-	6.9	5.7	2.0			2.5	1.50	2.1
660	68.7	forward	Mean	23.0	70.3	65.6	74.6	<0.05		9.5	9.40	23.4
			SD	-	6.8	0.8	4.0			3.1	0.50	2.6
		backward	Mean	22.3	71.7	66.0	76.4			9.8	10.0	20.7
			SD	-	7.6	0.9	3.6			2.4	1.00	2.1
***P*-value of ANOVA**						<0.05					<0.05	

According to Table 2, data of all turbine types were normally distributed. All variables were tested by paired t-test and it was clear that means $LAeq_{10min}$ of 300 kW and 660 kw turbines in both sides were significantly different (P<0.05) while in 550 kW ones (P=0.31). Mean of $LAeq_{10min}$ is 1.8 dBA was higher at the back of 660 kW turbines as compared with their forward. This difference is more than the 300 kW and 550 kW turbines. In higher frequencies, SPL is averagely 2 dBA more at the back of the turbines.

According to signal-to-noise ratio, there is high difference between minimum and maximum sound pressure levels. Signal-to-noise ratio is 0.7dBA lower at the back of 300 kW and 660 kW turbines than their forward, while for 550-kw turbines it is vice versa.

Post Hoc (LSD) test showed that means of $LAeq_{10min}$ were not different between 300 kW and 550 kW wind turbines (P=0.53), while 300 kW turbines $LAeq_{10min}$ mean has a significant difference with that of 660kW ones (P=0.05). $LAeq_{10min}$ was 660 kW turbines more than 300 kW and 550 kW wind turbines. Day average sound level (Ld) was higher for 660 kw turbines which is about 68.7 dBA. The minimum daytime average sound level (Ld) was related to 300 kw turbines.

Wind turbines produce broadband

aerodynamic noise which is similar to wind noise that is of low frequency; this type of noise has more penetration than the high frequency noise. According to C-weighted one-octave-band noise level, Fig.4 illustrates the noise frequency spectrum of each turbine type in the evening.

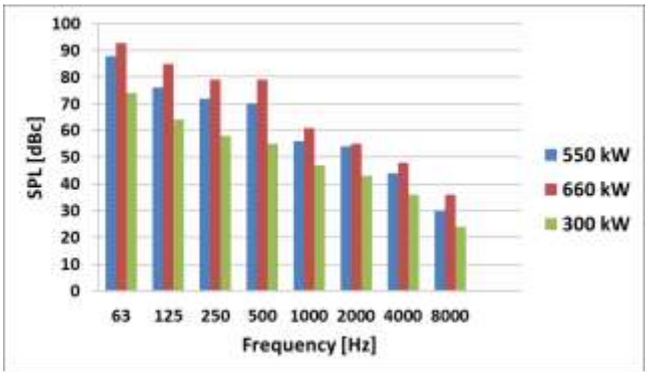

Fig.4. Noise frequency spectrum of three types of wind turbines (660, 550, 300 kW) in the evening

Wind turbine noise was more in low frequency range. The sound pressure levels of all turbine types decreased averagely towards higher frequencies. Statistical results showed that the wind speed and the sound pressure levels at all frequencies of one octave band, including 31.5, 63, 125, 250, 500, 1000, 8000 have a significant correlation (P <0.05), so an increase in wind speed leads to increase in sound pressure level in the central frequency. Results did not show a significant correlation between the sound pressure levels in frequencies of 2000 and 4000 Hz (P> 0.05). Therefore, the wind speed does not make changes the sound pressure levels at frequencies of 2000 and 4000. The sound pressure levels measured at in front and on the back of all types of turbines which don't have significant differences in the range of 250 Hz and lower (P>0.05). In higher frequencies, SPL is averagely 2 dBA more on the back of the turbines. The maximum wind speed occurs in the evening and the minimum speed in the morning.

Since the wind noise interference is decreased by the wind screen on the microphone of sound level meter and also measurement of sound characteristics carried out on the wind farm and there were neither automobile nor background noise in the wind farm, so the recorded noise was only belonged to the turbine blades.

Wind speed increase leads to increase of rotational speed of blades which generate noise. Fig.5 illustrates the relationship between wind speed and Leq_{10min} in three types of wind turbines.

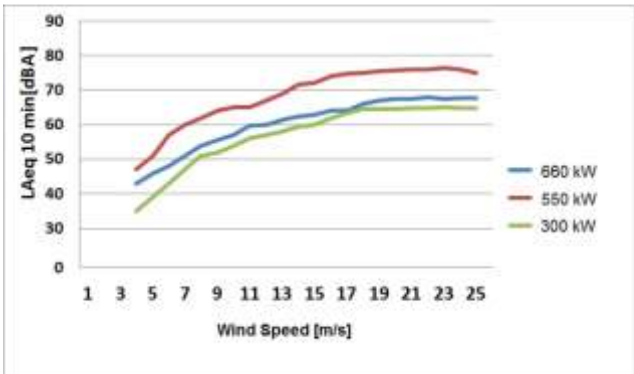

Fig.5. The relationship between wind speed and Leq_{10min} in three types of wind turbines (660, 550, 300 kw)

According to Fig.5, wind speed has approximately significant relationship with $LAeq_{10min}$ up to 17 m/s (P<0.001). Wind speed leads to increase of $LAeq_{10min}$ dramatically up to about 9 m/s. When wind speed increases from 9 m/s to 17 m/s, $LAeq_{10min}$ increases more gradually, although there is still significant relationship between them (P<0.05). The variation of $LAeq_{10min}$ in speeds higher than 17 m/s, is very slow and there are no significant relationship between wind speed and $LAeq_{10min}$ any more (P=0.3).

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between them (*P*<0.05). The variation of $LAeq_{10min}$ in speeds higher than 17 m/s, is very slow and there are no significant relationships between wind speed and $LAeq_{10min}$ any more (*P*=0.3).

DISCUSSION

Several factors such as wind speed, characteristics of turbine design, distance and ambient sound pressure level have effect on wind turbine's noise [1].

This research follows preparation of noise map to identify the wind turbine's noise emission patterns as well as wind turbine's noise measurements for understanding the sound characteristics of three types of wind turbines (300, 550 and 660 kw). According to environmental measurements, the daytime sound level (Ld) mean around the wind farm was 63 dBA. Also, on the noise map, there are four peak of Ld which three of them were located in the southern part of the map and showed that the number of 660-kW turbines were more in that part which consequently led to an increase in noise level. In Tickell C study, it was proved that the average noise emitted in wind farms should be less than 60 dB [2]. According to Tickell C study, daytime sound level (Ld) mean on this wind farm was 3 dB higher than the recommended level. This result is probably due to the blades of Manjil wind turbines which rotate with their maximum power at high wind speeds. Hence, aerodynamic noise is higher than recommendation level.

Clark C's study concluded that the 2-3 MW wind turbines in high speed rotation blade could emit 105-108 dB noise. However, the maximum noise (about 76 dBA) was related to 660 kw wind turbines in the current study [18]. The differences in emitted noise were due to the differences in turbine blade sizes. Turbines that have higher power and longer blades make clearly more noises by turbulence of air with their blades.

There were significant relationships between wind speed and $LAeq_{10min}$. Wind speed up to 17 m/s leads to an increase in $LAeq_{10min}$. However, there was no considerable variation in higher speeds. Bolin et al. assessed the wind turbines noise and found a non-linear relationship between wind speed and $LAeq_{10min}$. As wind speed had been increased up to 9m/s, $LAeq_{10min}$ would have been also increased, but it did not have any higher concerning changes [19]. Sound pressure level has a direct correlation with higher than 12 meters per second wind speeds [20]. These kinds of different relationships were due to the technical design of wind turbines; as the blades have limited resistance against rotation, the brake system gets activated and they would automatically remain at a steady speed in high winds in order not to be damaged. This mechanism would cause no exceed of certain limit in noise generated by motion of air around the blades. Some wind farms do not reach their maximum power in order to extend the wind turbines' lifetime and this has led to the difference among the values in different studies.

In the current study, wind turbine noise was higher in low frequencies. In a same study, authors researched on frequency analysis of different turbine sizes and also came to the conclusion that the similarity was because of the standard structure and similar functions observed for all types of blade turbines [2, 21]. Also, the other reason for finding the same result is the dominant voice caused by the air turbulence around the turbines which is similar to the low frequency wind noises.

Sound pressure level in the frequency range of <250Hz on both sides of the turbines do not have significant differences and are almost equal, but in higher frequencies, it is 2dBA more at the back of the turbines. The sound pressure level of all lower frequencies was higher at the back of wind turbines against our results as a result of larger blades and thicker structure and so the higher generation power [22]. The differences in results can be related to the low frequency noise which was amplified at the back of studied turbines and had an enhancing result on the blade's aerodynamic noise and consequently the sound pressure level at the back of the turbines was higher in low frequencies.

In the study, According to Signal-to-Noise Ratio, there were high differences between the minimum and maximum sound pressure levels (about 23 to 25 dBA). Also in a study, wind turbines noise had fluctuations [6]. The similarity in results can be related to the periodic rotation of turbine blades that was why wind turbine sounds could be heard intermittent.

According to our results, wind turbine's noise is an important environmental noise which residential areas exposure to. So, it can cause potential negative impacts on nearby residents' health.

CONCLUSION

Daytime sound level around the wind farm was higher than the recommended values. Wind turbine noise is more in low frequency ranges and fluctuating sound is also another feature of wind turbines noise. This type of noise has more penetration than the high frequency noise that it can cause potential negative impacts on the health.

Wind direction and turbine characteristics affect model of noise emission. Results showed that increasing turbines size causes increase in turbine height, blade length as well as increased aerodynamic noise from it. It was also concluded that wind speed has direct relationship with aerodynamic noise from the turbines. Of course, rotational speed of the blades to a certain extent was influenced by wind speed. It does not cause damage to the turbine blades and the noise does not exceed a certain limit.

Due to structural characteristic of wind turbines, we cannot reduce the noise at source. So, the automatic braking system for the lower speeds such as 9-12 m/s is recommended as a way to reduce the wind turbine noise. Also, since the wind turbine needs to be located in a free area of all boundaries, we cannot use shield between wind farm and residential area. Hence, we recommend using noise controllers. In receiver places and resistant windows needs to be changed with a double glazed window in order to prevent noise transfer and also, we propose the workers at the wind farm to use ear protection devises.

Due to the time limitation in the implementation of this pilot, the required measurements have been done in spring. The wind direction and speed have confirmed that the results might be different in the other seasons. So the weather condition can change the turbine blades emitted noise. It is recommended that more studies be conducted in cold seasons for more validation.

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