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Experimental and Theoretical Study on a Wind Energy Unit

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ABSTRACT
The conversion process in the wind turbine, from mechanical (kinetic) energy to electrical energy, is affected by many factors that increase or decrease the useful output of the wind energy convertor. In this paper, three factors were studied experimentally on a Horizontal Axis Wind Energy Unit "EEEC" in laboratory-scale. The aim of this experiment was to study the influence of the number of blades, the angle of attack and the incident angle on the wind energy unit parameters to optimize its efficiency. For this purpose, the effect of the number of blades was studied firstly, in order to select the number of blades where the maximum inputs obtained at lab ambient temperature 25 °C and atmospheric pressure. Then, different readings of the incident angle and angle of attacks were taken. The data was analyzed using Microsoft Excel software. The results show that the maximum parameters of wind unite energy that produce the maximum efficiency, namely: voltage (volt), current (ampere) and rotational speed (rpm) are obtained when the number of blades is 4, the incident angle is 0° (when the rotor direction is with wind direction) and the angle of attack is 75°. Finally, these results were implemented in a simulation program (HOMER software) that uses this turbine in a resident along with storage to cover the needs of a selected house.

Keywords: wind turbine, angle of attack, power curve

INTRODUCTION

Wind energy converters (WEC) harness the kinetic energy contained in flowing air masses. The energy conversion involves wind energy converting part of the wind power by reducing the wind speed. Wind energy converters are equipped with rotors to extract wind power, and consist of one or several rotor blades. The extracted wind power generates rotation and is thereby converted into mechanical power at the rotor shaft. Mechanical power is taken up at the shaft in the form of a moment at a certain rotation and is transferred to a machine (such as a generator or a pump). It is physically impossible to technically exploit the entire wind energy, as in this case the air flow would come to a standstill. Hence, the air would fail to enter the swept rotor area, and wind power would no longer be available [Heier 1998].

The relationship between the power extracted from the wind and the wind speed is cubic; which means any increase in the wind speed is reflected in the power extracted from the turbine to increase by about one and half [Heier 1998].

For wind energy converters, usually almost symmetrical profiles are applied, as they normally produce low drag for low angles of attack and thus almost no lift force. Lift and drag force increase along with the angle of attack ($\alpha > 0°$) [Heier 1998]. This was also investigated experimentally in this paper.

Wind energy converters require appropriate control mechanisms to limit power extraction at higher wind speeds, as well as increasing power extraction in slow wind condition or at start up. That is why it is important to understand the way power is controlled. In the scope of this study the blades are rotated to extract as much power as possible.

For a good performance of wind turbine an experimental investigation of the effect of number of blade and attack angle was conducted on horizontal axis wind turbines. The angles were (0–90°) with 15 degrees increase, finding that 75

Table 1. Abbreviations

A	Ampere
Cp	Power coefficient
DC	Direct current
G	Generator efficiency
I	Current (ampere)
Isc	Short circuit current
P	Power
Rpm	Revolution per minute
V	Voltage (volt)
W	Watt
α	Angle of attack

degrees is the best and (2-4) blade numbers are optimal [Asl et al. 2017].

Few studies on the factors that affect the efficiency of the conversion process in a Wind Energy Convertor (Horizontal axis), were made experimentally, while many studies were conducted on a real Wind Energy Convertor, which needed more time, effort and costs. However, the majority of research related to the factors influencing the performance of the horizontal wind energy converters is presented below. One of the studies focuses on the importance of the effects of the reduced frequency and phase difference on the aerodynamic loads, which can affect the wind turbine performance [Gharali et al. 2017]. The other shows that the design and number of blades are the most important parameters in optimizing the efficiency of wind turbines and the rotational speed is increased by increasing attack angle from 00 to 75 [Asl et al. 2017]. On the other hand, there was research on the optimization of the geometry of a wind turbine and investigating the influence of geometrical parameters on the performance of the turbine different turbulence intensities [Tahani et al. 2017]. Another experimental study aimed at optimizing the blade geometry for average wind speed 5 m/s based on operational Reynolds number and utilized the blade geometry. The result of this study shows that the design achieved in the research is more cost-effective and more wind energy is harnessed using equivalent swept area [Akour et al. 2018].

In addition, one of the studies was conducted on the blade direction and design, called "the blade element momentum method" [Kaltschmitt et al. 2007]. This improved method is used specially for umbrella-type rotor aerodynamics calculation. Another contribution involved the wind tunnel testing, which was elaborately schemed and conducted to examine the calculation precision. This study highlighted the importance of pitch angle selection in order to obtain the maximum power, as well as maintaining relative velocity within the acceptable limits for the turbine.

Furthermore, modeling the wind turbine is important to analyze the effect of the environmental changes such as wind speed and direction. The wind speed increases along with the rotor speed. This affects the turbine as the capacity limitations of the generator shall not be exceeded to avoid mechanical deterioration of the moving mechanical parts. On the other hand, the power generation shall be controlled accordingly. The change in the pitch angel by twisting the blade around its axes shall affect the angle of attack (wind direction). Consequently, our investigation validated experimentally that the optimal angle of attack is 750 [Asl et al. 2017].

METHODOLOGY

First, the experimental study was conducted to identify the effecting factors that increase or decrease the useful output of the wind energy convertor. Afterwards, the obtained results from our study were scaled up to determine the required area, power rating and hub height for a wind turbine to cover home consumption for (3) days. Finally, simulation was elaborated by using (HOMER software).

Experimental Setup

The Wind Energy Unit, "EEEC", contains a laboratory-scale aerogenerator, and is used to study the conversion of kinetic wind energy into electrical energy and to study the influence of some factors on this generation. The unit consists of a stainless-steel tunnel, an aerogenerator and an axial fan with variable speed (computer controlled). A rotor (or turbine) and a generator constitute the core elements of the aerogenerator. The air speed is varied by changing the rotational speed of the axial fan. This fan generates the air flow required to set the rotor of the wind energy unit. The generator converts the rotor's kinetic energy into electrical energy. The aerogenerator incidence angle and the angle of every blade can be modified. The blades can be removable and it is possible to set different blade configurations. The experimental apparatus is shown in Figure 1.

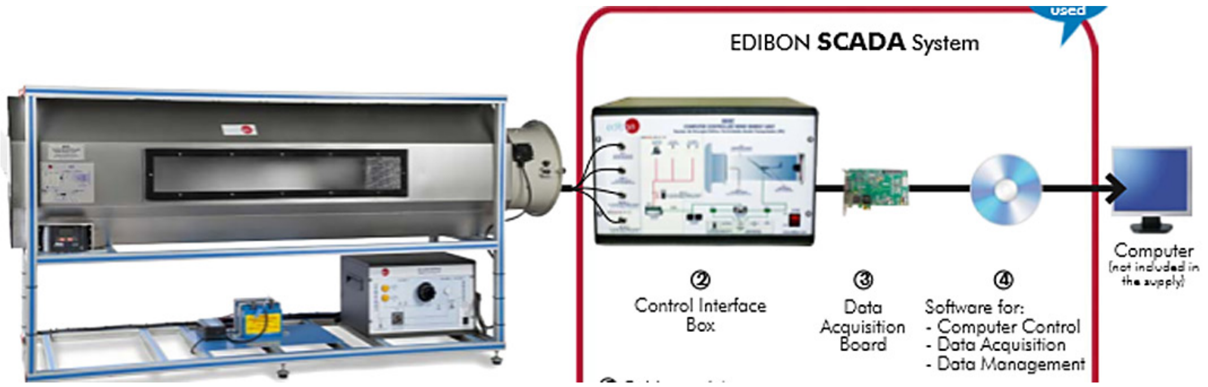

Fig. 1. Experimental apparatus

The apparatus is a stand-alone system without the interface segment.

This unit includes a DC Load Regulator, an auxiliary battery charger, a battery and a DC Loads module. The DC Loads module contains DC lamps, rheostat, DC motor, load selector and switches to select the type of load. The following parameters are measured: air temperature, air speed, speed of the rotor and voltage and current. A temperature sensor is located before the aerogenerator rotor. The air speed is measured with a sensor placed in the tunnel and the rotational speed of the aerogenerator (rpm) is determined as well. A voltage and current sensor allows measuring the voltage and current to determine the power. It is possible to measure, in real time, the value of the DC voltage and the current given by aerogenerator, before and after the regulator. Figure 2 illustrates the process diagram and process element allocations.

The unit comprises: stainless steel tunnel of 2000×550×550 mm approx. (78.74×21.65×21.65 inches approx.), which includes two transparent windows of 1000×130 mm approx. (39.37×5.11 inches approx.). Aerogenerator diameter: 510 mm. Starting air speed: 2.0 m/s max. Power output: 60 W. Voltage: 12 V max. Charging current: 5 A. It includes a set of six blades.

Experimental procedure

In order to identify the parameters affecting the wind turbine efficiency and performance, the setup is designed to be able to change wind

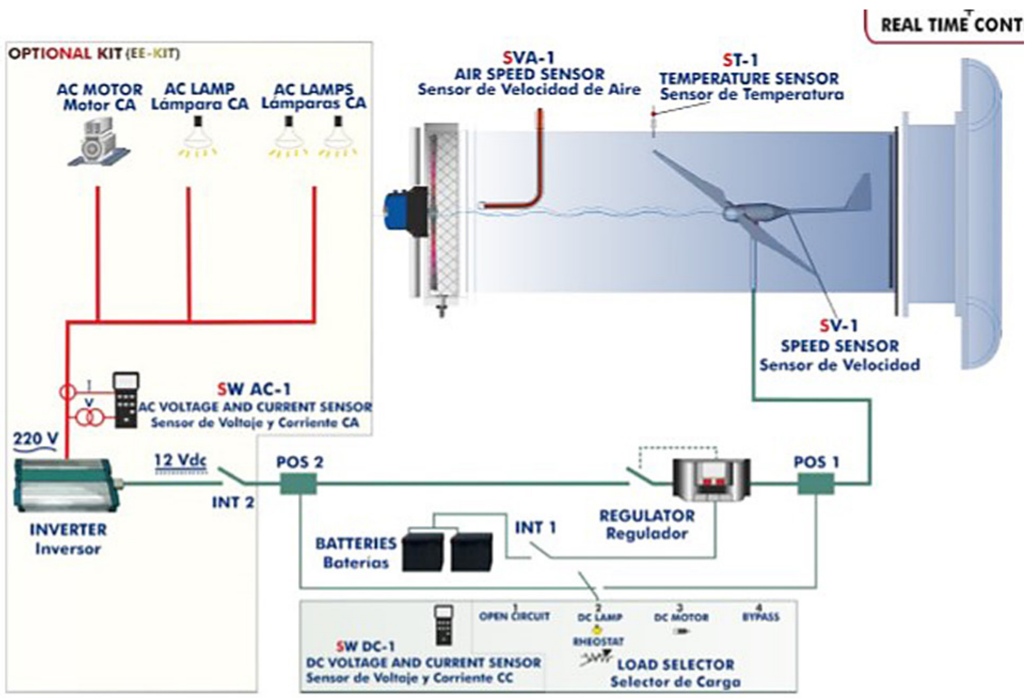

Fig. 2. Schematic diagram

speed, rotor incident angle, number of blades and angle of attack. This section contained the following parts:

1. Study of power generated by the aerogenerator depending on the incident angle. This part aims at determining the relation between the air incident angle and the captured by the rotor.
2. Study of power generated by the aerogenerator depending on the number of blades. The aim of this part is to study the effect of blade number on the rotational speed and output power. The fan speed is set to max, angle of attack – 90°.
3. Study of power generated by the aerogenerator depending on the angle of attack (blades). The aim of this part is to investigate the effect of attack angle on the rotational speed and output power, attack angles between 0 and 90° every 15° (0°, 15°, 30°, 45°, 60°, 75° and 90°) were tested.
4. Wind speed. This part aims at study the effect of wind speed on rotor speed (attack angle 75°).
5. Determining of the typical parameters of the aerogenerator. This part aims at determining the I-V curve and typical operational parameters (Isc, Voc and Pmax), by connecting the single-phase power supply. In this part, the load is a rheostat that is changed from the maximum value to the minimum value filling the following table. Note Isc was at the lowest rheostat value, Voc was obtained when the switch position is at position 1 (open circuit position). Tables and Figures are shown in the result section.
6. Determination of the maximum power output. The aim of this part is to determine the maximum power output at different air speed. We selected the DC load (rheostat) changing its value from max to min (attack angle 75°, (4) blades). The Pmax curve Vs air speed is shown in the results section.

RESULTS

The measurements were recorded, and Excel sheets used for the analysis to generate graphs. The result is clear since the optimal position of the rotor is in line with the flow direction. This is realized in the YAW systems. The max performance and the efficiency of the wind energy unit were obtained when the number of blades was (4). The Table 2–7 shows that the max performance as well as the efficiency of the wind energy unit was obtained when the angle of attack is (75°), where the number of blades is 4.

Table 2. Results of the study on the power generated by the aerogenerator depending on the incident angle

V wind (m/s)	I (A)	V (Volts)	Angle position (degree)	N (rpm)
6.4	0.04	3.3	0	245
Attack angle 90	Almost zero	0	+45	10
	Almost zero	0.1	25	20
	Almost zero	0	-45	10

Table 3. Results of the study on the power generated by the aerogenerator depending on the number of blade

V wind (m/s)	No. of blades	I (A)	V (Volts)	N (rpm)	Speed ratio
6.0	2	0.02	1.4	150	0.65
Attack angle 90	4	0.04	3.3	245	1
	5	Almost zero	0.1	50	0.2
	6	0.01	1.1	130	0.57

Table 4. Study on the power generated by the aerogenerator depending on the angle of attack (blades)

V wind (m/s)	Attack angle	I (A)	V (Volts)	Power (w)	N (rpm)
Max	0	zero	zero	zero	zero
	15	0.009	0.1	0.0009	79
	30	0.02	1.6	0.0062	162
	45	0.06	4.4	0.264	294
	75	0.17	11.6	1.972	645
	90	0.04	3.3	0.132	245

Table 5. Wind speed

V wind (m/s)	I (A)	V (Volt)	Rotor speed (rpm)
2.5	0.02	2	197
3	0.04	3.4	244
4	0.08	5.9	370
5	0.11	7.8	464
5.8	0.14	10.1	574

Table 6. Determining of the typical parameters of the aerogenerator

R position (%)	I (A)	V (Volt)	Air speed (m/s)
Max	0.09	12.7	6.2
75%	0.11	12.3	
50%	0.16	11.5	
25%	0.29	8.7	
Min	0.3	14.3	
Isc	0.3	Voc	14.4 V

Table 7. Determination of the maximum power output

Fan speed	Power (Watt)	Air speed (m/s)
Min	0.04	2.4
25%	0.136	3
50%	0.472	4
75%	0.858	5
Max	1.414	5.8

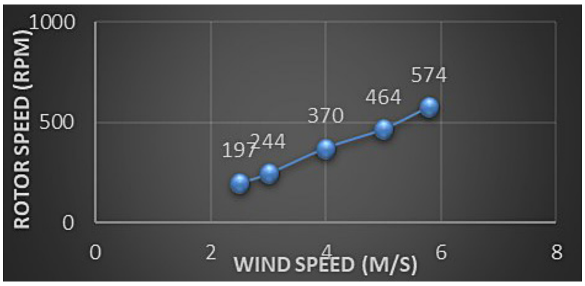

Fig. 3. Effect of wind speed on rotor speed (attack angle 75°)

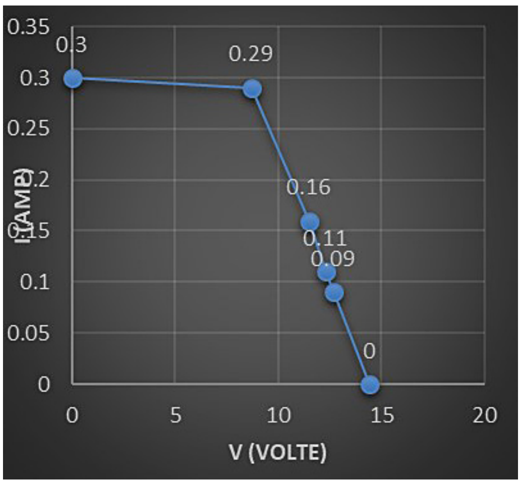

Fig. 4. I-V curve

The Figures 3–5 clarifies the relation between wind speed and rotor speed.

SCALING AND SIMULATION

The flow condition is the same in both large and small cases if the following criteria are met [Giahi and Dehkordi 2016]:

- The tip speed ratio is maintained in both cases.
- The blade profile and the number of blades are kept the same.
- Proportional adjustments are made to all dimensions containing radius, profile chord.

The Table 8 shows the relation between the power and the wind speed for small wind turbine.

Table 8. Power vs. wind speed for the small wind turbine

Power (Watt)	Air speed (m/s)
0.04	2.4
0.136	3
0.472	4
0.858	5

Cp =35%.
Generator efficiency G = 90%.
Mechanical power = Cp·wind power.
Electrical power = Cp·wind power·G.

An area of a wind turbine was calculated to cover a home consumption for (3) days, through scaling up our experimental results. The house model is shown in the Table 9.

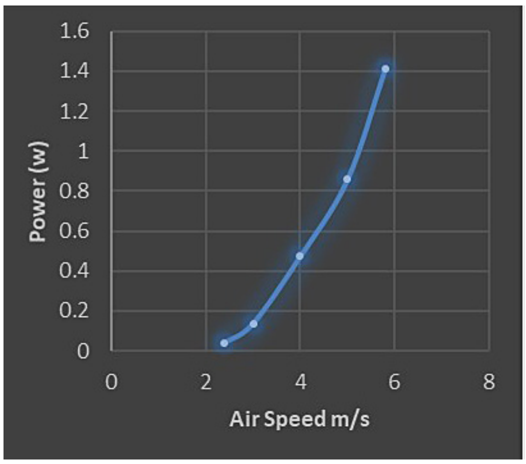

Fig. 5. Maximum power output at different air speed (4 blades, 75° degree)

Table 9. House model

Appliance	Power	No.	Avg hrs/day	Avg Wh/day
Light	11	8	3	264
TV	60	1	4	240
Computer	60	1	3	180
Refrigerator	80	1	24	1920
Kettle	1000	1	0.2	200
Microwave	700	1	0.4	280
Food processor	400	1	0.15	60
Washing machine	800	1	0.6	480
A/C unit	1000	1	2	2000
Total Wh/day				5624

Power required = 5624/24= 234.3 Watt
Average wind speed in Jordan = 4.76 m/s.
$234.4 = 0.35 \cdot 0.9 \cdot (1.22/2 \cdot (4.76)^3) \cdot \Pi \cdot r^2$
Diameter = 3.8 meter, this is the minimum diameter for the turbine.
Accordingly, the power vs. wind speed will be as follows: D = 3.8 meter.
Example:

$$P = 0.35 \cdot 0.9 \cdot (1.22/2 \cdot Vwind^3) \cdot \Pi \cdot (1.9)^2$$

Table 10. Power curve for the large turbine

Power (Watt)	Air speed (m/s)
30	2.4
58.9	3
140	4
273	5
470	6
748	7
2180	10
2902	11
0	12

Table 11. Turbine scaled parameter

Start speed	2 m/s
Cut off speed	12 m/s
Rated speed	5.6
Diameter	3.6 m
Rotational speed	650 rpm @ 5.7 m/s
Load per Year	2052.8 kWh
Turbine rated power	two values will be simulated 271.25 watt and 468.72 watt
Hub height	1, 2, 3, 4, 5 meters will be simulated

Table 12. Wind curve parameters

Air speed (m/s)	Power Watt (proposed 1)	Power Watt (proposed 2)
2.4	30	30
3	58.9	58.9
4	140	140
5	273	273
6	470	273
7	470	273
10	470	273
11	470	273
12	0	0

Table 13. System Sizing Results-Homer 2.68 Beta

<table>
<tr><th>Component</th><th>Quantity</th><th>Size</th><th colspan="2">Details</th></tr>
<tr><td>Wind turbine</td><td>1</td><td>0.470 kW</td><td colspan="2">Hub-height 5 m
AC
Rated wind speed 6 m/s</td></tr>
<tr><td rowspan="4">Battery</td><td rowspan="4">4</td><td rowspan="4">12 V
200 Ah</td><td>String size</td><td>4</td></tr>
<tr><td>Strings in parallel</td><td>1</td></tr>
<tr><td>Batteries</td><td>4</td></tr>
<tr><td>Bus voltage (V)</td><td>48</td></tr>
<tr><td>Converter</td><td>1</td><td>0.2 kW</td><td colspan="2"></td></tr>
</table>

HOMER software simulation parameters

The scaled turbine parameters are shown in the Table 11. The Table 12 shows the wind curve that was fed into the simulation and simulated as parametric table. The proposed (1) and (2) are two suggested wind turbines that differ in terms of the speed ratio (underlined value). Homer simulation was used to compare the best turbine.

HOMER software simulation results

The Figure 6 and 7 shows the system schematics. The Table 13 summarizes the size of the components.

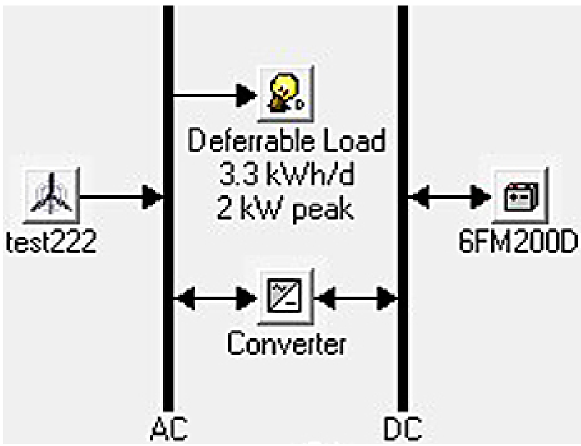

Fig. 6. System Schematic-Homer 2.68 Beta

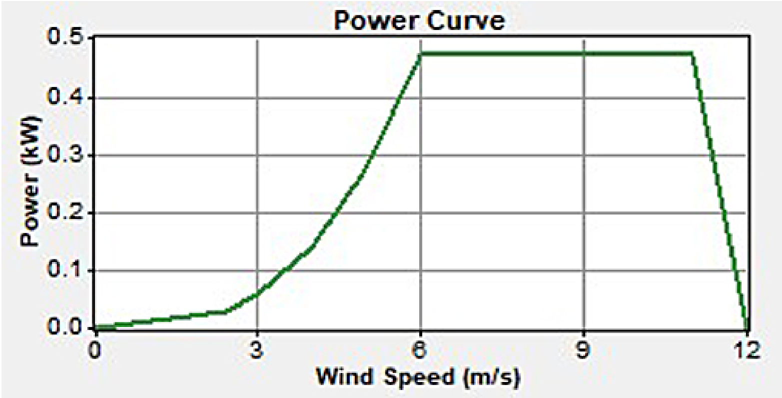

Fig. 7. Large Turbine Power Curve-Homer 2.68 Beta

CONCLUSIONS

After conducting the experimental study on the wind energy unit, we found that the maximum parameters of wind unit energy that produce the maximum efficiency are: voltage (volt), current (ampere) and rotational speed (rpm), obtained when the number of blade is (4), the incident angle is 0° degree (when the rotor direction is with wind direction) and the angle of attack is 75° degree. Moreover, the experimental study gave us the chance to manually alter the pitch angle in order to increase the angle of attack easily.

In addition, in our paper, we had the chance to emulate the wind speed available in Amman in order to determine the best design parameters for the wind turbine. Most importantly, it was possible to manually alter the pitch angle in order to increase the angle of attack to increase the power extracted from the turbine, then implement the result in a program, simulating real conditions for a residential load backed up with appropriate storage.

The simulation results show the adequate sizing for the whole system; wind turbine rated power was 0.470 KW at rated wind speed 6 m/s (slightly higher than the average wind speed in Amman). Additionally, it shows the height of the hub is 5 m.

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