COMPARATIVE STUDY OF VERTICAL AXIS WIND TURBINE AND HORIZANTAL AXIS WIND TURBINE

National Science Fair Project Report

Level : *Middle Level*

Category : Physical Science

Submitted by

M.ABDUL MAZID

(Grade VIII)

ARRAHMAAN INTERNATIONAL SCHOOL

(Creating the community of Excellence)

COMPARATIVE STUDY OF VERTICAL AXIS WIND TURBINE AND HORIZANTAL AXIS WIND TURBINE

CONTENTS

COMPARATIVE STUDY OF VERTICAL AXIS WIND TURBINE AND HORIZANTAL AXIS WIND TURBINE

ABSTRACT

Limited fossil resources, daily increasing rate of demand for energy and the environmental pollution fact have made people revert to renewable sources of energy as a solution. Alternative energy sources are a big deal these days. One such source is the wind. I planned to find out how vertical axis wind turbine and horizontal axis wind turbine can use the power of the wind to generate energy and compare the efficiency of both the turbines by designing different number of blades using aluminium metal sheet, ACP sheet and PVC pipes. I used fan as the wind source and digital multimeter to measure voltage.

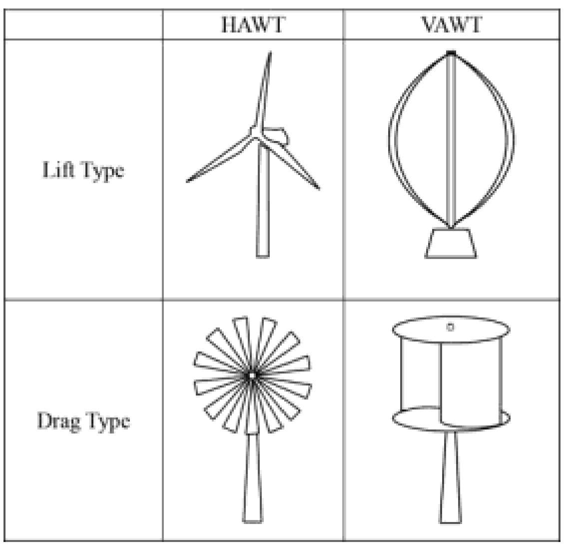
Through my research I found in vertical axis wind turbine, VAWT with 4- blades generates more current and voltage compared to other blades. Next to 4-blades, VAWT with 5 blades, VAWT with 3 blades and then comes the VAWT with 2-blades. VAWT with 5-blades and VAWT with 3-blades don’t show much variation in output. 2-blades generates the least output. In Horizontal axis wind turbine**,** HAWT with 3-blades generates more current output and HAWT with 2-blades generates more voltage output compared to other blades. HAWT with 5-blades generates minimum output. I understand that in HAWT as the number of blade increases the output decreases. But the turbine rotates very fast when it has minimum number of blades.

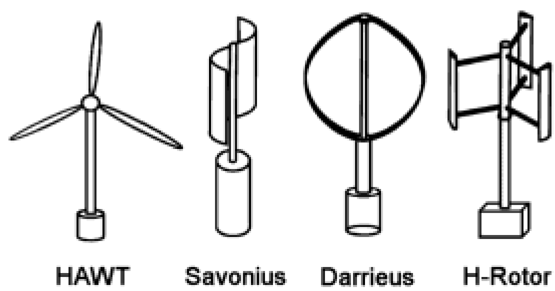
Through my comparative study I concluded that the horizontal axis wind turbine is efficient that vertical axis wind turbine in case of power output. Among all the blades tested 3-blades HAWT gives the maximum output. In HAWT as the number of blade increases the output decreases but in VAWT as the number of blade increases the output seems to be increases.

The blades of HAWT rotate very fast compared to the VAWT when equal speed of wind is given. The advantage of horizontal wind is that it is able to produce more electricity from a given amount of wind. So if you are trying to produce as much wind as possible at all times, horizontal axis is likely the choice for you. The disadvantage of horizontal axis however is that it is generally heavier and it does not produce well in turbulent winds.

INTRODUCTION

The wind has its kinetic energy as it nothing but the flow of atmospheric air. A wind turbine is a machine which utilizes the kinetic energy of wind to produce rotational mechanical energy in its shaft. The rotational motion of the shaft turns an electrical generator to generate electricity. Generally, wind turbines can be classified by application, capacity, blade number, relative position of rotor shaft to ground, type of aerodynamic forces generated by blade, and so on. Among them, the relative position of rotor shaft to the ground and the aerodynamic forces of blade are the two main ways for classification of wind turbine. According to the relative position of rotor to ground, wind turbines can be classified into horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). According to the force type of the blade, wind turbines can be classified into lift-type wind turbines and drag-type wind turbines.





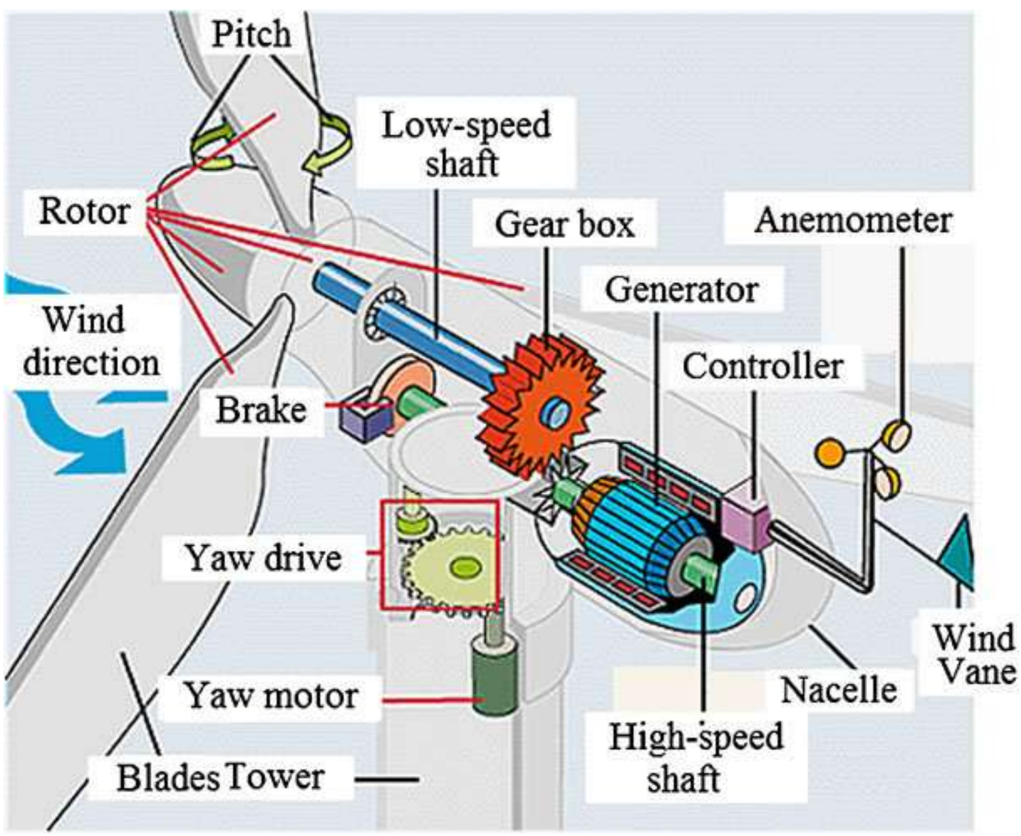
Design

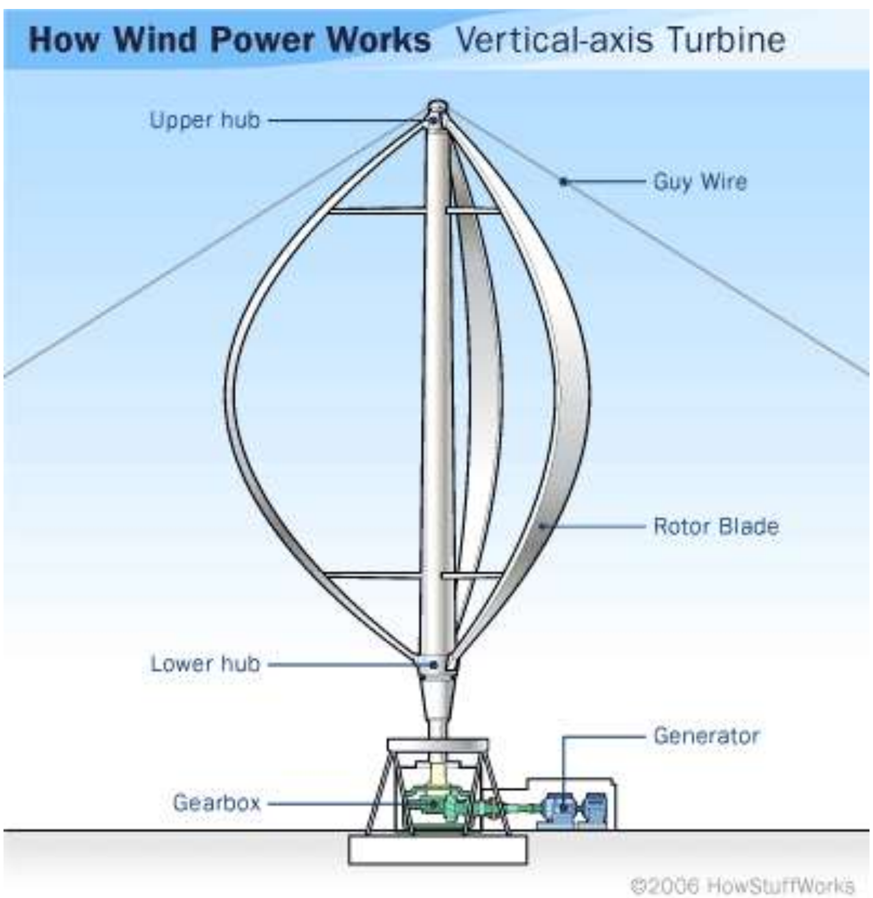
Horizontal Axis Wind Turbine (HAWT) is the most commonly used design configuration in wind turbines with rotors similar to that of aircraft rotors. In HAWTs, the rotating axis of the blades is parallel to the direction of the wind. Vertical Axis Wind Turbine (VAWT), on the other hand, is probably the oldest type of windmills in which the axis of the drive shaft is perpendicular to the ground. It is a type of windmill where the main rotor shaft runs vertically, as opposed to the horizontal axis wind turbine.

Machinery

The horizontal axis wind turbines have the entire rotor, gearbox and generator mounted at the top of the tower, which must be turned to face the wind direction. A significant advantage of vertical axis wind turbine over horizontal axis type is that the former can accept wind from any direction and thus no yaw control is needed. In VAWTs, the wind generator, gearbox and other main turbine components can be set up on the ground, which simplifies the wind tower design and construction and consequently reduces the turbine cost.

Components of HAWT

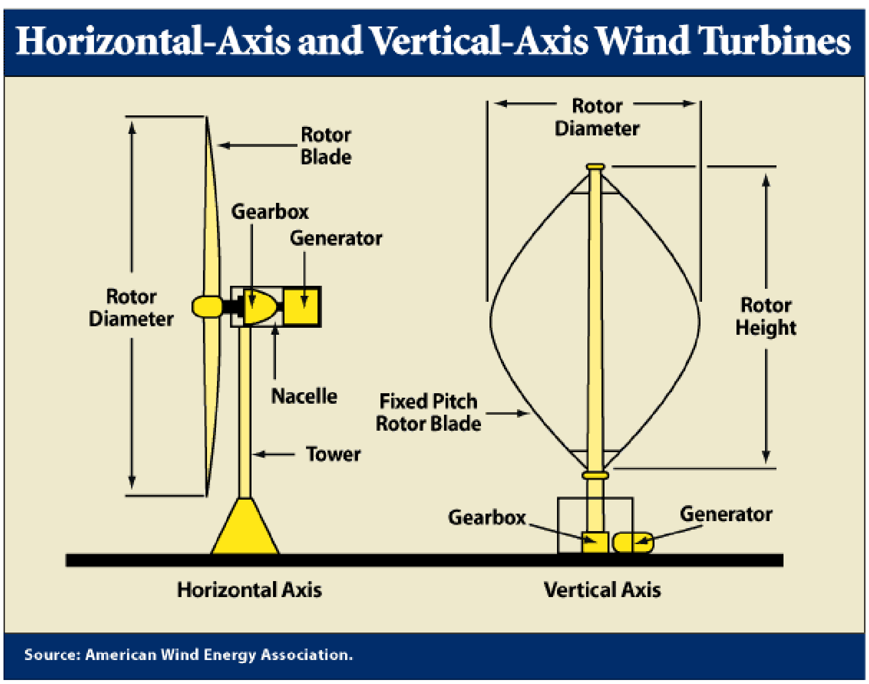



How Wind Power Works Vertical-axis Turbine
Upper hub
Guy Wire
Rotor Blade
Lower hub
Generator
Gearbox
©2006 HowStuffWorks

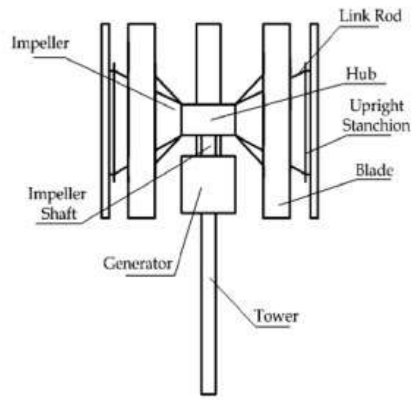
The Features of Structure:

As to the Horizontal axis wind turbine, during the process of one circle of rotation of the blades, the blades receive the combined effects of inertial force and gravity, the direction of the inertial force is subject to change, while that of the gravity is stable ever, so that the blades suffer an alternating load, which is very detrimental to the fatigue strength of the blades. Besides, the generator of the Horizontal axis wind turbine is about tens of meters far away from the ground, which brings a lot of troubles to repair and maintain the generator.

As to the Vertical axis wind turbine, during the process of rotation of the blades, the condition of receiving effects is better than that of the Horizontal axis wind turbine, because the directions of the inertial force and gravity keep stable ever. Therefore, the blades receive a fixed load, and accordingly the fatigue longevity is longer than the Horizontal axis wind turbine. At the same time, the generator of the Vertical axis wind turbine is often placed under the rotor or on the ground, and so it is easy for repair and maintenance.



(a)



(b)

The Starting Wind Speed:

It is commonly admitted that the Horizontal axis wind turbine enjoys a good starting performance. But according to the gas-hole experiment practiced by China Aerodynamics Research and Development Centre (CARDC) on the small-sized Horizontal axis wind turbine, the starting wind speed is usually in the range of 4~5 m/s, and the maximum has been up to 5.9 m/s. this starting performance obviously can't be satisfactory.

In the field of wind turbines, it is also commonly said that the Vertical axis wind turbine suffers a bad starting performance, especially the Φ structure of Darrieus wind turbine, which has no initial starting ability to speak of. This is also an obstacle on the way of the development of the Vertical axis wind turbine. Nevertheless, as for the H structure of Darrieus wind turbine, it has an opposite conclusion. As long as the airfoil and installing angle are selected appropriately, the wind turbine can gain quite satisfactorily starting performance. Considering the air-hole test, the H structure of Darrieus wind turbine can start at a wind speed of 2m/s, which is undoubtedly preferable than the Horizontal axis wind turbine.

Wind Direction and Speed

To work properly, the horizontal-axis turbine needs the wind to flow at a right angle to the blades. If it blows from a different direction than the blades are facing, the turbine gets much less energy from the wind. To accommodate changes in wind direction, the turbine has a yaw drive that rotates the unit's direction. However, the drive adapts slowly to changing directions because it must turn the entire turbine and propeller assembly. By contrast, a vertical turbine runs well regardless of wind direction, making it better-suited to urban areas with tall buildings where wind turbulence is a given. The vertical-axis design allows it to operate on lower wind speeds than is possible with the horizontal turbine.

Wind Energy Efficiency

Horizontal-axis turbines convert more of the wind's energy into useful mechanical motion because the blades are perpendicular to wind direction, and the blades pick up the energy throughout their range of movement. By comparison, the blades on a vertical-axis turbine suffer an efficiency disadvantage, capturing energy from the wind only on the front side; at the rear part of their rotation, they drag on the system.

Mechanical Complexity and Stress

Because it requires a yaw mechanism to adjust to changing wind direction, the horizontal-axis turbine is mechanically more complex than the vertical design. Gyroscopic effect comes into action when axis of rotation of a rotating body (propeller, wheel etc) is turned round in a plane perpendicular to plane of rotation of that body. The gyroscopic action of the spinning blades of a horizontal-axis turbine produce stress when the yaw mechanism turns to catch the wind. Over time, the stress can crack the turbine blades and hub. The vertical-axis turbine does not experience this stress.

Suitable Location

The horizontal turbine's tall tower and long blades work well only in wide-open spaces. Vertical turbines are generally much more compact and can be placed on building rooftops and other urban locations with fewer restrictions. The vertical unit's low height also makes it suitable for areas where wind picks up speed between buildings or over hilltops.

Market Preference

Although the vertical-axis turbine has some advantages over the horizontal design, more large-scale energy developers have chosen the horizontal-axis layout, leaving vertical-axis generation to small commercial operators or individuals. The horizontal axis is simpler to understand and meets the expectations of what a wind turbine should look like. Vertical-axis generators have historically been the object of exaggerated claims, causing skepticism for potential investors of the technology.

The Environmental Problems:

Although the wind is called as the clean energy, and can be friendly to the environment, with more and more large-scale wind power farms being built, some environmental problems caused by the wind turbines have been also prominent. These problems are mainly reflected in two aspects: first, the noise problem; second, the negative impact on the local ecological environment. The tip speed ratio of the Horizontal axis wind turbine is generally about 5 to 7, and at such a high speed, the blades cutting the air flow will produce loud aerodynamic noise, and meanwhile many birds through such high-speed blade are difficult to escape.

The tip speed ratio of the Vertical axis wind turbine is usually 1.5 to 2, which is much lower than that of the Horizontal model. Such low rotating speed basically can't produce aerodynamic noise, and completely mute the noise. The benefits of muteness are apparent, because it solved the difficult that in the past the wind turbine couldn't be erected in some circumstances, such as urban public facilities, residential areas, etc. With this regard, it can be got that the Vertical model will enjoy a wider field of application than the Horizontal model.

The benefits brought by the low tip speed ratio are not only the environmental advantages, but also beneficial to the overall performance of the wind turbines. Based on the aerodynamic analysis, the faster the object, the greater the impact of the shape of outlook on the flow field. When the wind turbine runs in the outdoors, the blades are inevitably contaminated by the pollution, and the pollution can actually change the shape of the blades. In terms of the Horizontal model, even if this kind of change to the blades is trivial, it can also reduce the energy utilization. But as for the Vertical model, its rotating speed is quite low, so it is not so sensitive to the change of the shape, which means that the contamination to the blades has no effect on the aerodynamic performance of the wind turbine.

Horizontal Axis Wind Turbine Vs Vertical Axis Wind Turbine Comparision Chart

Horizontal Axis Wind Turbine	Vertical Axis Wind Turbine
The rotating axis of the blades is parallel to the direction of the wind.	The rotating axis of the blades is perpendicular to the direction of the wind.
The main rotor shaft runs horizontally in HAWTs.	The main rotor shaft runs vertically in VAWTs.
HAWTs are generally used under streamline wind conditions where a constant stream and direction of wind is available.	VAWTs are mainly beneficial in areas with turbulent wind flow such as rooftops, coastlines, cityscapes, etc.
The rotor faces the wind stream to capture maximum wind energy.	The rotor can accept wind stream from any direction.
Inspection and maintenance is difficult in HAWT.	Inspection and maintenance is easy.
HAWTs extract more power from wind.	VAWTs extract less power from wind.
They are more efficient than VAWTs.	They are less efficient than HAWTs.
They operate fine in moderate wind speeds.	They can operate even in low wind speeds.

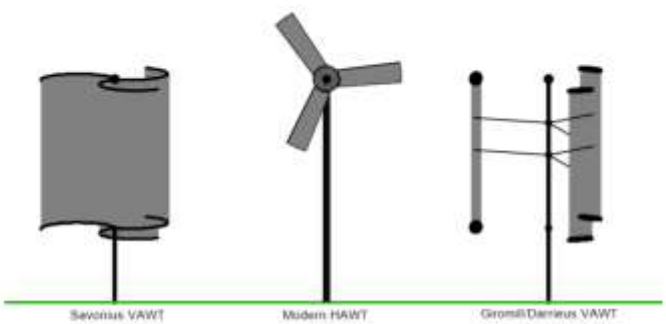
The Comparative Parameters:

Number	Performance	Horizontal axis	Vertical axis
1	Power generation efficiency	50% - 60%	Above 70%
2	Electromagnetic interference	YES	NO
3	Steering mechanism of the wind	YES	NO
4	Gear box	Above 10KW:YES	NO
5	Blade rotation space	Quite large	Quite small
6	Wind-resistance capability	Weak	Strong (it can resist the typhoon up to 12-14 class)
7	Noise	5-60dB	0-10dB
8	Starting wind speed	High (2.5-5m/s)	Low (1.5-3m/s)
9	Ground projection effects on human beings	Dizziness	No effect
10	Failure rate	High	Low
11	Maintenance	Complicated	Convenient
12	Rotating speed	High	Low
13	Effect on birds	Great	Small
14	Cable stranding problem	YES	NO
15	Power curve	Depressed	Full

Courtesy: http://www.windturbinestar.com/hawt-vs-vawt.html.

STATEMENT OF THE PROBLEM

The stock of fossil fuels on that planet is becoming nil day by day, so there is a significant need for renewable sources of energy to produce electricity to meet up the on-growing demand for electricity. The wind power generating station is one of the solutions for that. The wind power generating stations use many giant wind turbines to produce required electricity. The wind turbines can have either horizon shaft or vertical shaft depending on their design criteria. We can see the wind turbines mostly in coastal areas. I want to research how effectively we can use the wind energy as an alternative source of electricity in urban areas too. So I decided to have a comparative study of both the VAWT and HAWT efficiency by designing different number of blades.



HYPOTHESIS

Vertical axis wind turbine with 5 blades generates high voltage compared to horizontal axis wind turbine.

DESIGN OF STUDY

Step 1:	Step 2:
INDEPENDENT VARIABLE: • Number of blades **DEPENDENT VARIABLES:** • Voltage and Current **CONTROLLED VARIABLES:** • Base Stand • Dynamo • Wind Speed • Materials used to design blades • Dimension of blades	**INDEPENDENT VARIABLE:** • Axis of Turbine (VERTICAL AXIS WIND TURBINE AND HORIZONTAL AXIS WIND TURBINE) **DEPENDENT VARIABLES:** • Voltage and Current **CONTROLLED VARIABLES:** • Base Stand • Dynamo • Wind Speed • Materials used to design blades • Dimension of blades • Number of blades

MATERIALS:

- Aluminium metal plate
- ACP Sheet
- Dynamo12 Volt (2)
- PVC Fitting pipe -6
- Elbow pipe -8
- Connecting wires
- Multimeter
- L-Clamp (28)
- 1" PVC pipe
- Cycle screws (50)
- Dynamo fitting PVC pipe -2
- Cello tape
- Wooden piece

- Ruler and Pencil
- Table top fan

Tools needed

- Drilling machine
- Angle grinder
- Hacksaw blade
- Scissor
- Screw Driver

PROCEDURE:

VERTICAL AXIS WIND TURBINE (VAWT)

1. Cut 4 squares of side 6cm from the ACP sheet which will be used to fix to the shaft of dynamo.
2. Cut the aluminium metal sheet into 14 pieces (14 blades) each of which is 10cm length and 5cm breadth using a strong scissor.
3. Then make holes on the aluminium blade using drilling machine for connecting the L-clamps.
4. Take 2 L-clamps and fix 2 aluminium blades either side with cycle screw nut and tighten that using screwdriver.
5. Make holes on the opposite sides of ACP Sheet to connect the L-Clamps fixed with metal blades.
6. Make a small hole at the center of the ACP square sheet so that it can fix to the shaft of the dynamo.
7. Repeat the step 3 to 6 for 3, 4, 5 number of blades. Be careful while fixing the number of blades at equal distance.
8. Now Vertical axis wind turbine is ready with different number of blades.

HORIZONTAL AXIS WIND TURBINE (HAWT)

1. Cut 4 squares of side 6cm from the ACP sheet which will be used to fix to the shaft of dynamo.
2. Cut the aluminium metal sheet into 14 pieces (14 blades) each of which is 10cm length and 5cm breadth using a strong scissor.

3. Then make holes on the aluminium blade using drilling machine for connecting the L-clamps.
4. Take 2 straighten-clamps and fix 2 aluminium blades either side with cycle screw nut and tighten that using screwdriver.
5. Make holes on the opposite sides of ACP Sheet to connect the straighten-Clamps fixed with metal blades.
6. Make a small hole at the center of the ACP square sheet so that it can fix to the shaft of the dynamo.
7. Repeat the step 3 to 6 for 3, 4, 5 number of blades. Be careful while fixing the number of blades at equal distance.
8. Now Horizontal axis wind turbine is ready with different number of blades.

Turbine Base

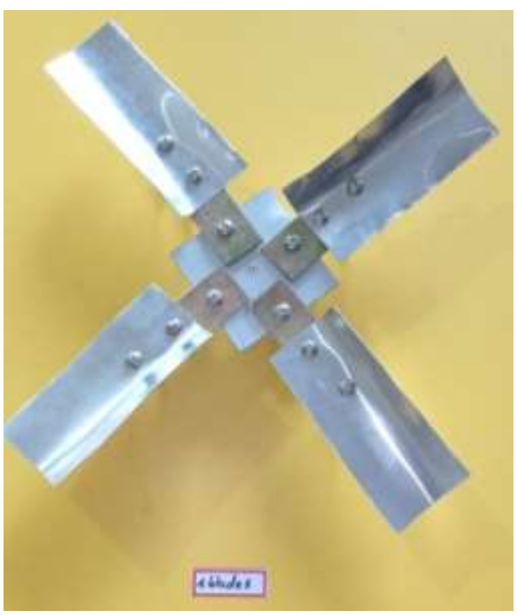
1. Make separate base for Vertical axis and Horizontal axis wind turbine.
2. Take small pieces of PVC pipes, PVC elbow pipe-8 and T-fitting pipe-6 for two stands.
3. Join these components together to make two turbine bases.
4. Take two dynamos and fix the dynamos separately on wind turbine bases.
5. These bases can be used for all the number of blades (VAWT blades & HAWT blades separately)
6. Fit the blades on the wind turbine base and use a table top fan to give wind to the wind turbine.
7. Change the blades and measure the output voltage and current using multimeter for both VAWT and HAWT.

Analyze the results:

- Analyze the efficiency of different number of blades in both VAWT and HAWT by blowing wind using a fan.
- Organize the data in graphs. On ‘X’ axis, plot the number of blades and on ‘Y’ axis plot the current in amperes and voltage in volt (separate graph).
- By plotting the graph like this we can analyse the efficiency of vertical axis wind turbine and horizontal axis wind turbine and the effect of number of blades.

COLLECTION OF DATA

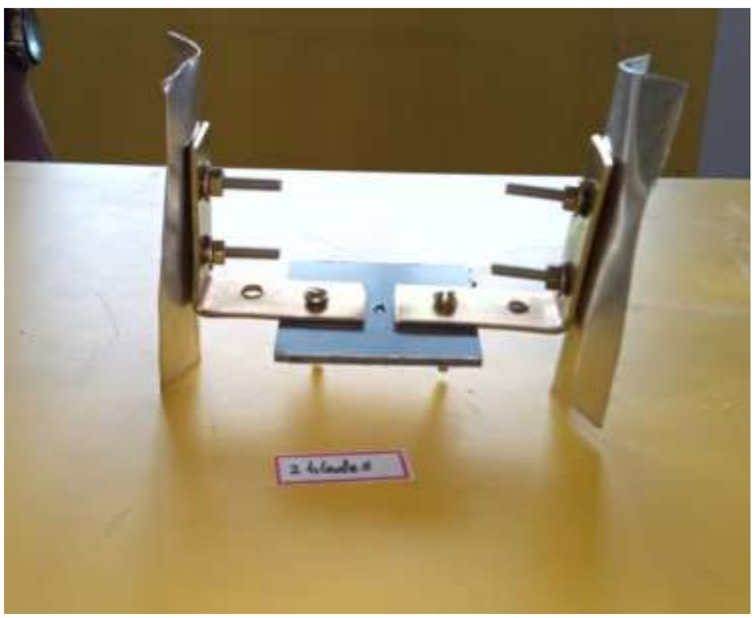
PHOTOGRAPHS

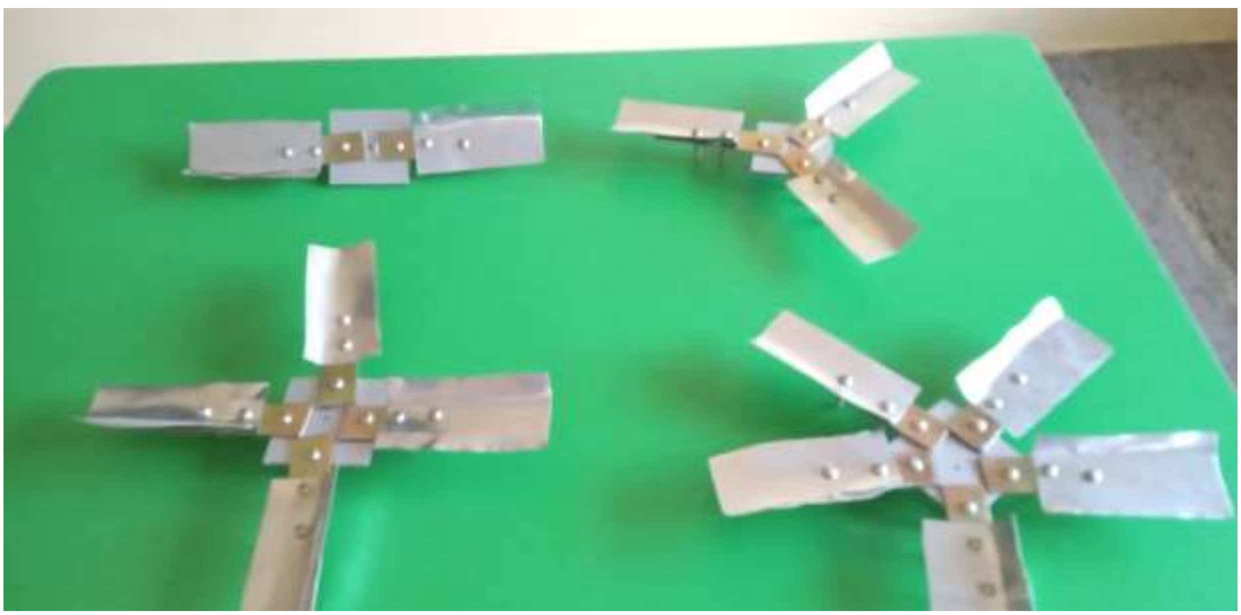



4 blades


5 blades


3 blades


2 blades





TABULATION

COMPARITIVE STUDY OF VERTICAL AXIS WIND TURBINE AND HORIZONTAL AXIS WIND TURBINE BY CHANGING THE NUMBER OF BLADES

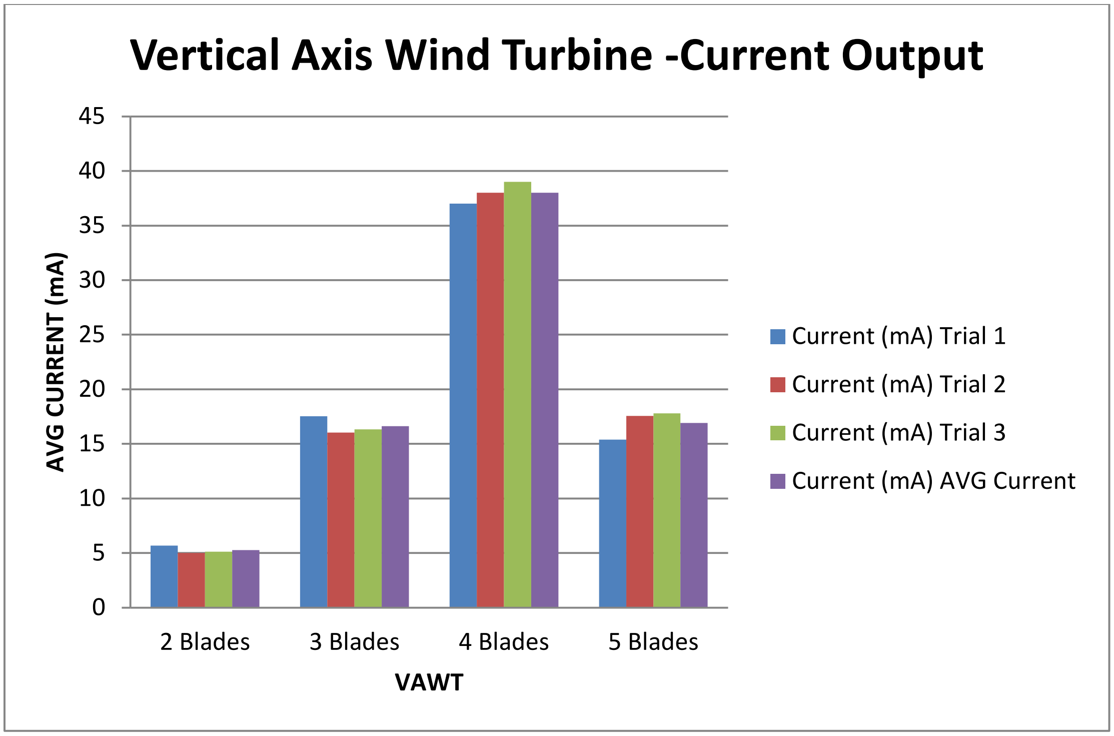
EFFECTS OF NUMBER OF BLADES IN VERTICAL AXIS WIND TURBINE

No Of Blades	Current (mA)				Voltage (V)			
	Trial 1	Trial 2	Trial 3	AVG	Trial 1	Trial 2	Trial 3	AVG
2 Blades	5.69	5.01	5.11	5.27	0.19	0.21	0.25	0.22
3 Blades	17.54	16.04	16.33	16.63	0.37	0.40	0.39	0.39
4 Blades	37	38	39	38	0.56	0.56	0.54	0.53
5 Blades	15.38	17.55	17.79	16.90	0.41	0.42	0.40	0.41

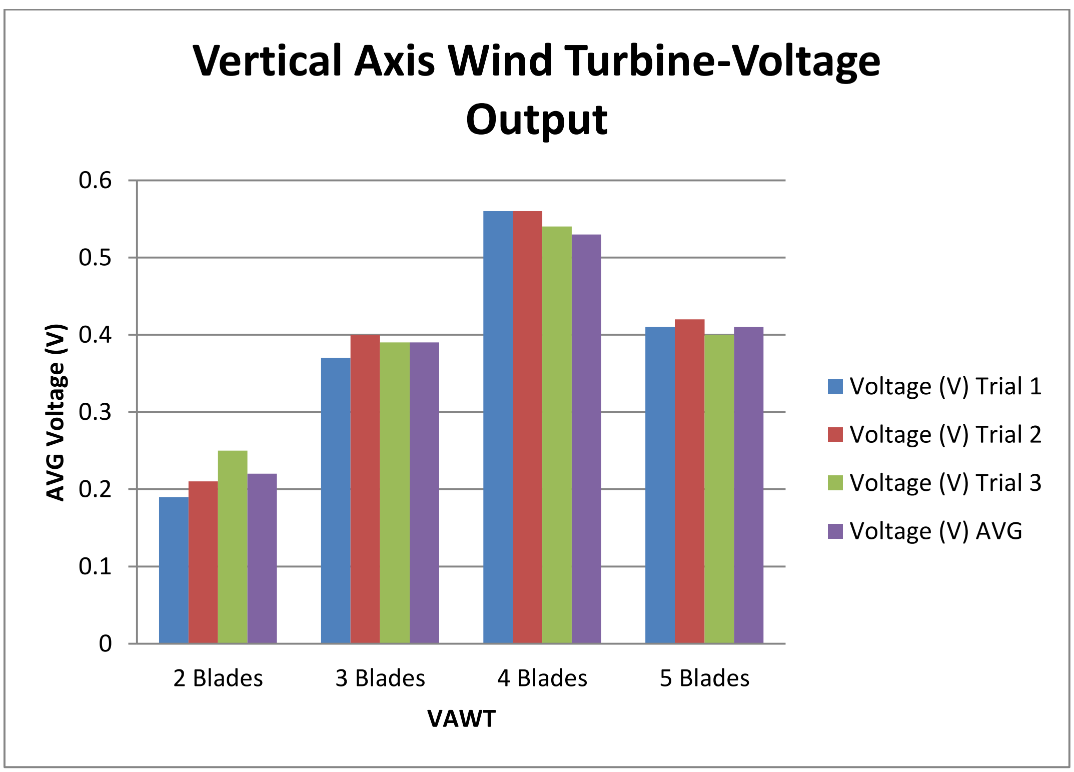
EFFECTS OF NUMBER OF BLADES IN HORIZONTAL AXIS WIND TURBINE

No Of Blades	Current (mA)				Voltage (V)			
	Trial 1	Trial 2	Trial 3	AVG	Trial 1	Trial 2	Trial 3	AVG
2 Blades	195.5	178	163	178.83	2.78	2.84	2.56	2.73
3 Blades	193	198	187	192.67	2.34	2.56	2.38	2.43
4 Blades	165	179	169	171	2.15	2.28	2.25	2.23
5 Blades	121	118	116	118.33	1.60	1.55	1.52	1.56

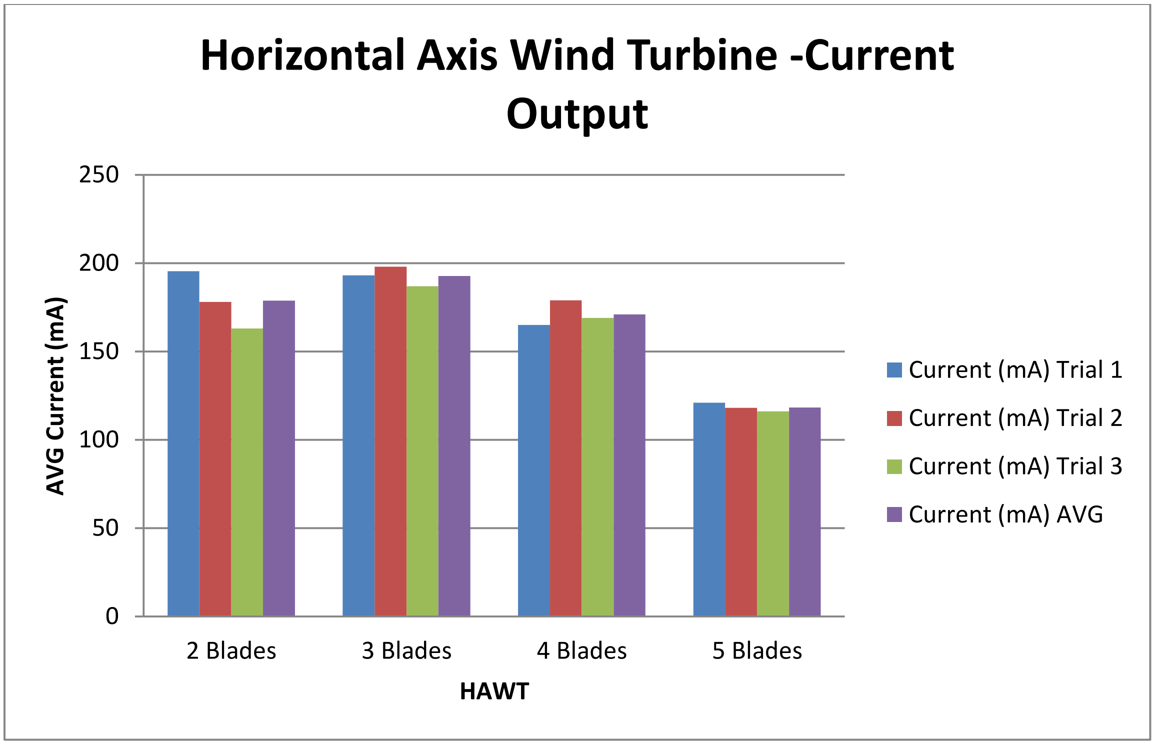
GRAPHS

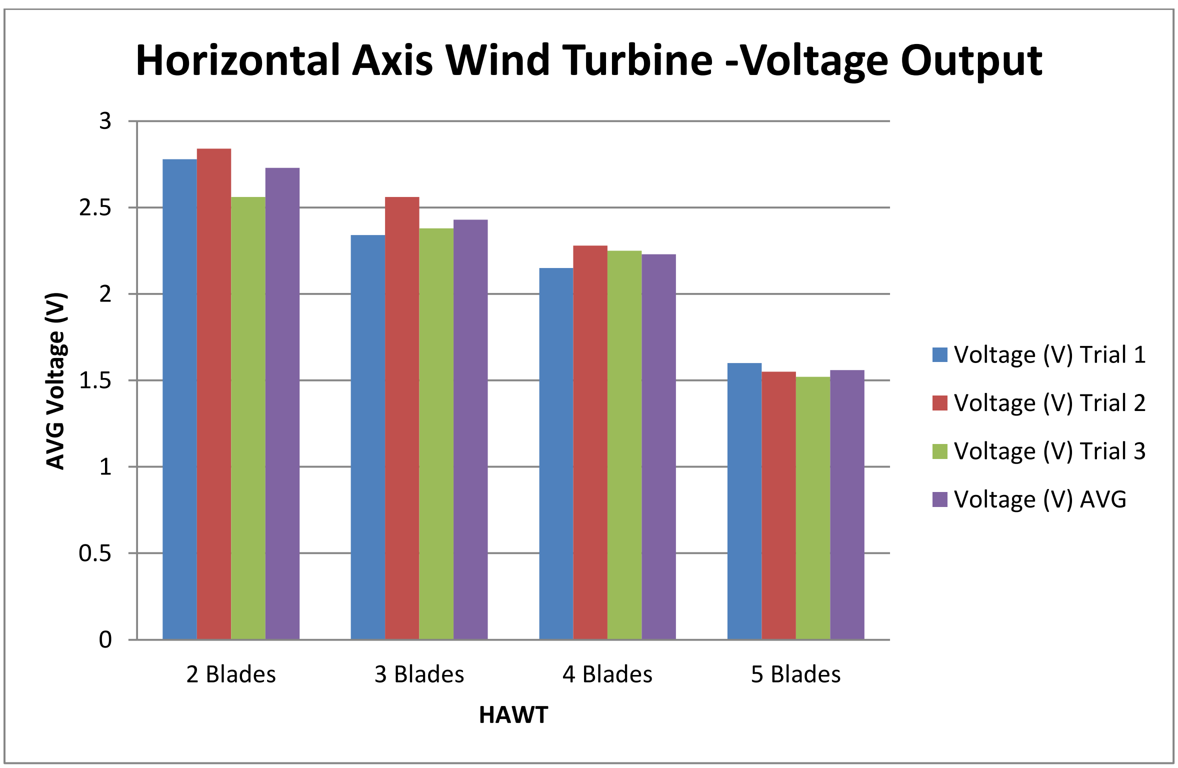


Vertical Axis Wind Turbine -Current Output
AVG CURRENT (mA)
45
40
35
30
25
20
15
10
5
0
2 Blades
3 Blades
4 Blades
5 Blades
VAWT
Current (mA) Trial 1
Current (mA) Trial 2
Current (mA) Trial 3
Current (mA) AVG Current

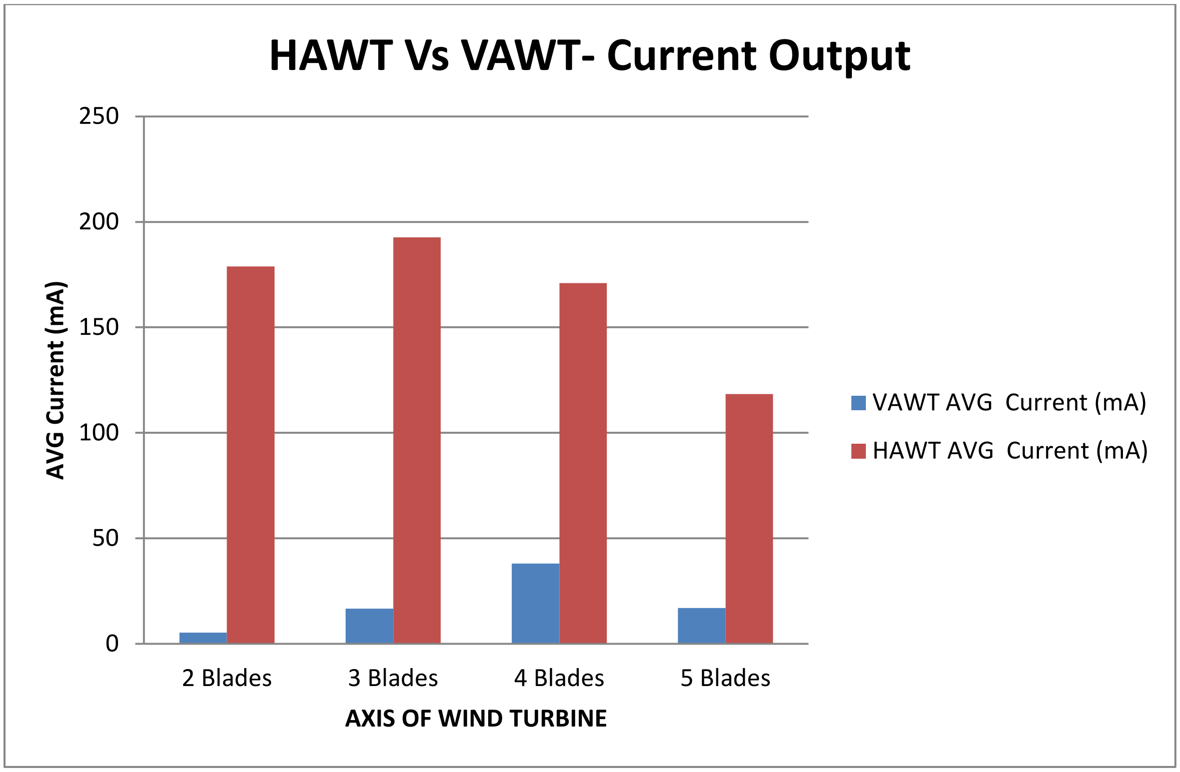


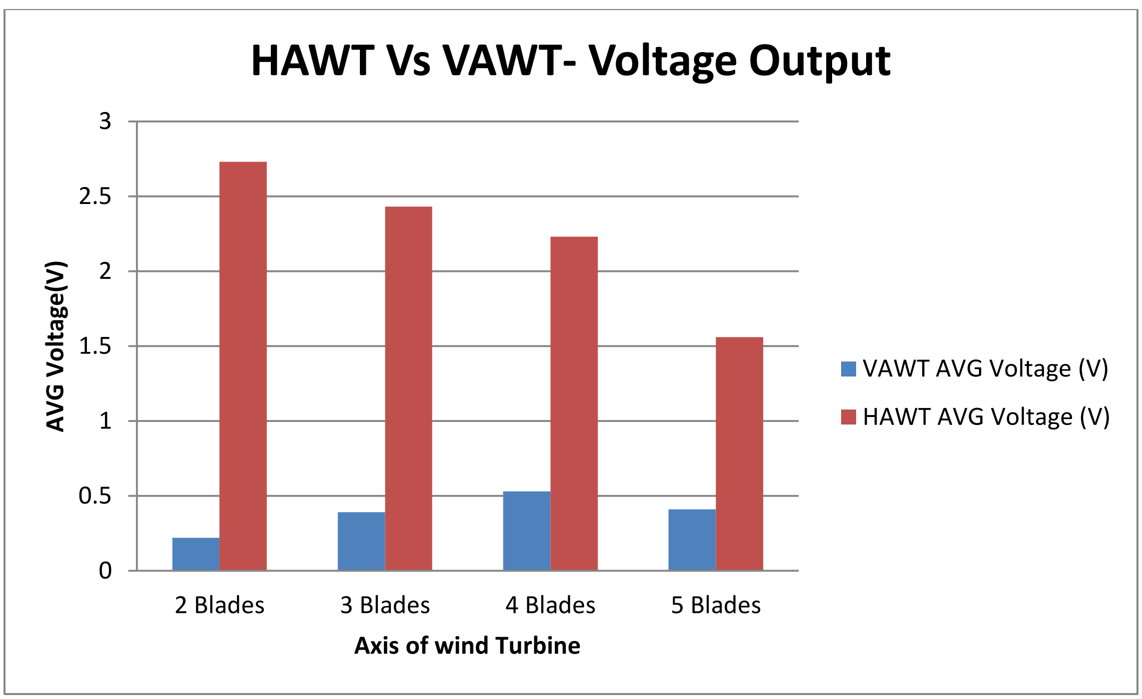
Vertical Axis Wind Turbine-Voltage Output
AVG Voltage (V)
0.6
0.5
0.4
0.3
0.2
0.1
0
2 Blades
3 Blades
4 Blades
5 Blades
VAWT
Voltage (V) Trial 1
Voltage (V) Trial 2
Voltage (V) Trial 3
Voltage (V) AVG


Horizontal Axis Wind Turbine -Current Output
250
200
150
100
50
0
AVG Current (mA)
2 Blades
3 Blades
4 Blades
5 Blades
HAWT
Current (mA) Trial 1
Current (mA) Trial 2
Current (mA) Trial 3
Current (mA) AVG


Horizontal Axis Wind Turbine -Voltage Output
3
2.5
2
1.5
1
0.5
0
AVG Voltage (V)
2 Blades
3 Blades
4 Blades
5 Blades
HAWT
Voltage (V) Trial 1
Voltage (V) Trial 2
Voltage (V) Trial 3
Voltage (V) AVG

COMPARISION OF VAWT AND HAWT EFFICIENCY





RESULTS AND DISCUSSION

- ***Vertical axis wind turbine:*** In vertical axis wind turbine, VAWT with 4- blades generates more current and voltage compared to other blades. Next to 4-blades, VAWT with 5 blades, VAWT with 3 blades and then comes the VAWT with 2-blades. VAWT with 5-blades and VAWT with 3-blades don't show much variation in output. 2-blades generates the least output.

  VAWT Blades Efficiency rating: 4-blades>5-blades>3-blades>2-blades

- ***Horizontal axis wind turbine:*** HAWT with 3-blades generates more current output and HAWT with 2-blades generates more voltage output compared to other blades. HAWT with 5-blades generates minimum output.

  HAWT Blades Efficiency rating: 3-blades>2-blades>4-blades>5-blades

  Through my research I understand that in HAWT as the number of blade increases the output decreases. But the turbine rotates very fast when it has minimum number of blades.

- ***Comparing VAWT & HAWT:*** Through my comparative study I concluded that the horizontal axis wind turbine is efficient that vertical axis wind turbine in case of power output. Among all the blades tested 3-blades HAWT gives the maximum output. In HAWT as the number of blade increases the output decreases but in VAWT as the number of blade increases the output seems to be increases.

- The blades of HAWT rotate very fast compared to the VAWT when equal speed of wind is given. The advantage of horizontal wind is that it is able to produce more electricity from a given amount of wind. So if you are trying to produce as much wind as possible at all times, horizontal axis is likely the choice for you. The disadvantage of horizontal axis however is that it is generally heavier and it does not produce well in turbulent winds.

- Vertical axis turbines are powered by wind coming from all 360 degrees, and even some turbines are powered when the wind blows from top to bottom. Because of this versatility, vertical axis wind turbines are thought to be ideal for installations where wind conditions are not consistent, or due to public ordinances the turbine cannot be placed high enough to benefit from steady wind.

APPLICATION

- Wind energy is primarily used for power generation. Wind power conversion systems have been increasingly employed in the U.S., Europe, India, and more sparingly in some other locations over the last decade, due to the development of technology that allows relatively high efficiency of the wind resource conversion.
- The key process is the conversion of the kinetic energy of moving air into the mechanical kinetic energy of rotating shaft of the turbine. Similar to solar energy resource, one of the main challenges with wind power is its intermittence and high variability, which requires systematic adjustments in operation as well as strategies to integrate the wind power into the grid.
- The wind power generation systems have been commercialized for several decades now. The efficiency and durability of the systems was improved over time. So, recent developments explain the growing interest in wind energy and observed growth of wind energy market.
- Economic analysis of renewable energy systems mainly focuses on the ability of the system to pay back the initial investment and operation costs within a reasonable period of time.
- The lifetime cost of the wind energy system can be split into the (i) initial cost for system manufacturing and installation, (ii) operating and maintenance cost, and (iii) decommission cost.
- The initial upfront cost of wind energy system is usually the highest (~75%) and typically includes turbine (including rotor, tower, drivetrain), foundation, land rent, electrical equipment, connection to the grid, road construction and other infrastructure, transportation, installation labor and expertise, and associated soft costs.

CONCLUSION

- My hypothesis "Vertical axis wind turbine with 5 blades generates high voltage compared to horizontal axis wind turbine" has been proven false.
- Both types of turbines, whether VAWTs or HAWTs, are used for generating electrical power from the wind. This work has compared both types, and also presented the advantages and disadvantages of both types.
- Each type has its applications. It depends on the wind speed and place to be fixed on. In spite of so many advantages over HAWT, we do not use VAWT for bulk power generation as the power output is quite less in VAWT compared to HAWT.

FUTURE ENHANCEMENT

- Through my current investigation I compared both VAWT and HAWT and I learned VAWT gives output during unsteady wind conditions. Moving forward I want to store the power output from the wind turbine in a battery and use the power battery instead of UPS, which is an uninterruptible power supply or uninterruptible power source. In other words I want to build an electrical apparatus that provides emergency power using the wind energy to a load when the input power source or mains power fails.

ACKNOWLEDGEMENT

The success and final outcome of this project required a lot of guidance and assistance from many people and I am extremely privileged to have got this all along the completion of my project. All that I have done is only due to such supervision and assistance and I would not forget to thank them next to the Almighty.

I respect and thank Mr. Sathakkathullah, for providing me an opportunity to do the project work. I am extremely thankful to Mrs. Sameem M.Sc, B.Ed for providing such a nice support and guidance throughout my project.

I owe my deep gratitude to my project guide Ms.Karthikai Selvi M.Sc, M.Phil who took keen interest on my project work and guided all along, till the completion of our project work by providing all the necessary information for developing a good system.

I would not forget to remember my parents for their encouragement and more over for their financial support and guidance till the completion of my project work.

BIBLIOGRAPHY

- https://www.electrical4u.com/wind-turbine-introduction/
- https://www.windpowerengineering.com/vertical-axis-wind-turbines-vs-horizontal-axis-wind-turbines/
- https://www.windturbinestar.com/hawt-vs-vawt.html
- https://education.seattlepi.com/horizontal-vs-vertical-wind-turbines-3500.html
- https://www.sciencedirect.com/topics/engineering/horizontal-axis-wind-turbine
- http://www.differencebetween.net/technology/difference-between-horizontal-and-vertical-axis-wind-turbine/
- https://epress.lib.uts.edu.au/student-journals/index.php/PAMR/article/view/1461/1539
- http://www.jocet.org/vol4/254-H0020.pdf
- https://windexchange.energy.gov/small-wind-guidebook