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Simulation of Train Induced Forced Wind Draft for Generating Electrical Power From Vertical Axis Wind Turbine (VAWT)

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Singapore's lack of ideal geographic location and natural resources created the need to generate renewable energy to offset its carbon footprint. The characteristics of the wind in tropical climates, which is turbulent flow in multiple directions, encouraged the use of the Vertical Axis Wind Turbine (VAWT), but the natural wind conditions are not feasible to power the VAWT due to inconsistencies in wind speed and direction. Exploring forced ventilation situations, it can either use a mechanically ventilated exhaust or wind energy recovery from accelerating objects. Mass Rail Transport (MRT) trains, the electrical rail system in Singapore, has high mass while accelerating at high velocity. This is why it is capable of producing large draft of increased air velocity. The simulation results from FLUENT ANSYS show that the forced wind draft is of laminar flow (up to 6 m/s) at the sides of the MRT train and diversifies to turbulent flow (up to 8 m/s) at the front face of the MRT due to the drag force. The laminar flow will enable the wind turbine to accelerate the spin momentum of VAWT supporting a greater energy output. The understanding of the vertical profile of wind speed specifications of wind turbines, has led to an invention of a unique idea of integrating a hydraulic lift in the main body of the wind turbine to maximize its potential of harvesting wind energy at greater altitudes due to increase in wind speed by 6%. From the movement of MRT trains, the energy that can be harvested from wind using a 2kW vertical axis wind turbine is calculated as 600,000 W/year. Based on simulation, with a 5 meter increase in the height of the turbine, the efficiency of power generation increases by 0.2 percent.

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1. Introduction

Burning of the fossil fuel is leading to the release of greenhouse gases at an increasingly rapid rate.[1] Even though there is an increase in usage of natural gas, being classified as the cleanest fossil fuel in the generation of electricity, the impact of the pollutants released into the atmosphere cannot be disregarded as these adversely impact the delicate balance of the biosphere. More effective and efficient methods to generate power are to be devised. Since time immemorial wind energy has been used to generate electricity to supply power for the functioning of the economy worldwide.[2] There is an increasing need for innovative methods to address the issues encountered in harvesting wind energy.

Such issues are on a larger scale in the tropical climates as the wind speed and direction is considered to be inconsistent.[3] Singapore being a small island with minimal natural resources is dependent on neighboring countries to supply power to support its economy. As the wind conditions are rather turbulent in this island, there are possible locations wherein harvesting wind energy from fast moving trains can be implemented.

More than 90% of the global electricity generated is contributed by the usage of coal and natural gas.[4] There definitely has to be reduction in the dependence on this source. Over the past few years, various methods have been implemented to harvest energy from forced ventilated conditions. Currently, various research projects are in progress, to study how the return air from the air conditioning systems can be used to provide wind energy for countries with unreliable wind characteristics.[5] And it has been proven that an average wind speed of 5 m/s is sufficient to generate power.[6]

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2. Review

2.1 Wind characteristics in Singapore

The wind speed on an average in Singapore is about 5-6 m/s. The wind experienced is unsteady as there are irregularity in speed and direction.[3] Wind is strongly influenced by the roughness parameters (roughness length) due to the large number of elements that contribute to the "roughness" such as high raised buildings and skyscrapers.[7] The roughness length is 0.6 – 1.6 meters approximately. There are inherent frictional effects on the envelope of air close to the ground surface. The presence of undisturbed air as the altitude increases, causes the wind to be steady and in a particular direction. Such a condition is highly feasible to the generation of power using wind turbines. Thus, due to steadiness of wind profile at higher altitudes, there is an increased efficiency with which electricity can be generated and is a more viable option.

2.2 Trains at high velocity produce large wind draft of increased air velocity

Drag, which is at times called air resistance, refers to forces that oppose the relative motion of an object through a fluid. For a solid object moving through a fluid, the drag is the component of the net aerodynamic or hydrodynamic force acting opposite to the direction of movement.

An object with high mass accelerating at high velocity is proven to produce large draft of increased air speed in the region of the object. This can be seen from the simulation study using Computational Fluid Dynamics (CFD) software. It is observed that the air flow is turbulent in nature caused by the large cross sectional area of the front face of the train with high drag coefficients; which is due to the drag force. This can prove the increased wind speed at the side walls of the train due to the high velocity of trains. It is understood that drag force is dependent on the speed of the object relative to the fluid. Since the flow is turbulent at the front face of the MRT train, we can conclude that the drag force is also high.

The drag force is given by the equation, $F_D = \frac{1}{2}\rho\vartheta^2 C_d A$, where F_D is the force of drag, ρ is the density of the fluid, ϑ is the speed of the object relative to the fluid, C_d is the drag coefficient and A is the reference area. The density of air is assumed to be 1 kg/m^3. Since the velocity of the train is high and so is the reference area, we get a very high value of the drag force. In addition, the drag coefficient (Cd) of a normal passenger train is about 1.8 or higher.[8]

2.3 The Wind Turbine

There are mainly two types of wind turbines, drag type and lift type. The drag types of wind turbines have already been outdated. Darrieus (lift) type wind turbines are in common use in this modern age of wind power generation. There are disadvantages to VAWT in comparison to the Horizontal Axis Wind Turbine (HAWT). Main disadvantages of VAWT are the inability of the turbine to self-start, lower in efficiency in comparison to HAWT and VAWTs undergo the fatigue cycle in every rotation. But VAWT is gaining recognition in the research field due to its' intrinsic advantages and diversified applications.[9] The advantages of the VAWTs are their ability to accept wind from any direction and the ability to provide direct rotary drive to a fixed load.

The HAWT usually has blades designed in a twisted or tapered fashion for optimum performance. The complexity in the design of the blades is reduced in the case of VAWT as the blades are of uniform cross section and are easy to fabricate. Furthermore, as the VAWTs are installed at the ground level in comparison to the HAWT the maintenance of all the components is easily facilitated.[10] Still several challenges remain for VAWT. Since it should be able to withhold the immense forces in turbulent conditions, changes in design specifications are required in the design of the wind turbines. Research to address this is being carried out.[11] For instance, the propeller blades need to be redesigned to be suited for implementation. Sturdy materials with high strength and durability have to be used while integrating the hydraulic lift for elevation.

2.4 Method for implementation

There are numerous forced ventilated situations including ventilated exhaust from air conditioning systems.

Most countries around the world have widespread rail networks wherein this technology can be implemented without the requirement of drastic changes to the infrastructure. The maximum efficiency with wind energy production is 59.26% which is also known as the Betz Limit.[12,13] Wind energy recovery from accelerating objects has to be such that the efficiency of the object is not affected.

The kinematic movement of the train causes turbulent wind profile due to aerodynamic drag forces and a VAWT working under such condition will operate at low efficiency. An optimum distance can be determined to minimize the effects of turbulent wind flow. This will enable the turbine to tap onto the laminar flow of wind draft created due to the low pressure areas around the train as it speeds by. The VAWT should be installed close to the train stations so that it does not hinder or increase the power required by the trains to maintain its optimum operating speed. Hence the ideal place to install the VAWT would be at distances where the speed of the train is high, but still outside the limit of the breaking distance from the station when the train starts decelerating. This in turn will result in increasing the braking efficiency of the trains in operation as the turbine will obstruct the even air flow patterns around the MRT train, thus reducing the power required to brake to a halt.

Since the approximate direction of the wind can be estimated from the results of the simulation study, the magnitude of the forces acting on the VAWT blades can be calculated. Depending on the wind condition of a particular place, research can be conducted to calculate the extreme levels of forces that would impact the turbine. This is important in deriving the design specifications required to build a sturdy wind turbine with a hydraulic lift in the main body to withstand large force and continue operating at maximum efficiency.

3. Simulations

3.1 Characteristics of MRT

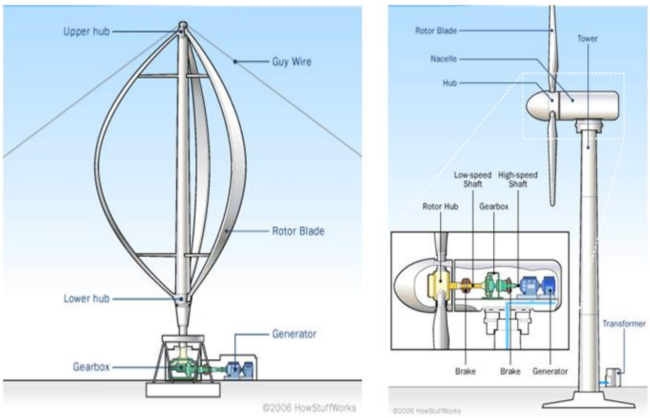
The below characteristics of the MRT trains and their frequency are considered for the simulations.

Listed parameters are from the information provided by the train operators in Singapore and by conducting on-site measurements for wind speeds.

3.2 Computational Fluid Dynamics Study using FLUENT ANSYS

A computational fluid dynamics study was conducted using the physical modeling software FLUENT ANSYS to calculate the flow and turbulence of wind profile from the movement of the trains. This study is essential to find the wind speed and directions to approximate the wind power that can be harvested from the wind turbines installed along the tracks of the trains. This also helps in finding the ideal location of the wind turbines as the wind profile from the kinematic movement of the trains is not consistent in the vicinity of the train stations. Factors such as building and trees in the near locality have to be taken into account as it plays a big role in bringing unsteadiness to the wind.

For the simulation study, the train was considered to be a cuboid of length 22.8 meters as represented in Figure 1. Simulations were conducted for the VAWT at height of 15 meters and 20 meters. The latter being for the situation wherein a hydraulic lift has been introduced in the main body of the wind turbine. The concept behind introducing the hydraulic lift is that more energy can be collected at greater altitudes. The extension of the main body of the turbine is in usage during the night from 2300 hours to 0600 hours when the trains are not in operation. The power generated here is depicted for a 2kW VAWT. The wind speed obtained from the simulations due to the kinematic movement of the trains is at 6 m/s.



(a) (b)

Fig. 1 Illustration of Vertical-Axis Wind Turbine (VAWT) and Horizontal-Axis Wind Turbine (HAWT) (from howstuffworks.com)

Table 1 Parameters for the attributes of MRT trains

	Parameters
Speed of Train	25 meters/second
Wind speed induced	6 meters/second
Annual Operation time	6197 hours
Annual Operation time	371820 minutes
Frequency of train at the station	5 minutes
Annual frequency of train	74364 times
Natural ventilation exposure	2563 hours (2300-0600 hours)
Length of Train	22.8 meters
Time to take for 1 train pass by	0.5 minutes
Total energy generation time (minutes)	37182 minutes
Total energy generation time (hours)	620 hours
Open air MRT stations are at a height	15 meters

3.3 Results and Discussions

Figure 2 represents the wind speed frequency distribution for natural wind speed distribution and forced ventilated wind speed distribution in addition to the natural wind speed distribution. At a wind speed of 6 m/s, the frequency of occurrence of wind is higher due to the forced wind draft and this is high due to increased frequency of trains passing by. Frequency can also be represented as, number of hours per year. The total energy generated over a span of a year can be found by the summation of power generated for the velocity distribution when multiplied with the frequency at respective speeds over the entire range of the distribution. Thus the wind energy generated is not only dependent on the power generated by the turbine at a particular wind speed, but also depends on the wind speed frequency distribution at the location of the VAWTs.

The wind power that can be generated in Singapore is represented in the Figure 3. Here again the theoretically available energy at wind speed of 6 m/s is more than 900,000 Watt per year. This is again higher in the case of forced ventilation compared to naturally ventilated conditions. The power curve of a 2kW VAWT shows that energy of more than 900,000 W can be generated at wind speed of 12 m/s. At 6 m/s the energy generated per year is 600,000 Watt.

Figure 4 depicts the comparison of the wind speed profile at a height of 15 meters and 20 meters.

The wind profile characteristics from the simulations show that the wind is strongly influenced by the roughness parameters (roughness length) in cities such as Singapore due to large roughness elements such as high buildings and skyscrapers.[7] The frictional effects on the envelope of air closest to the ground surface,

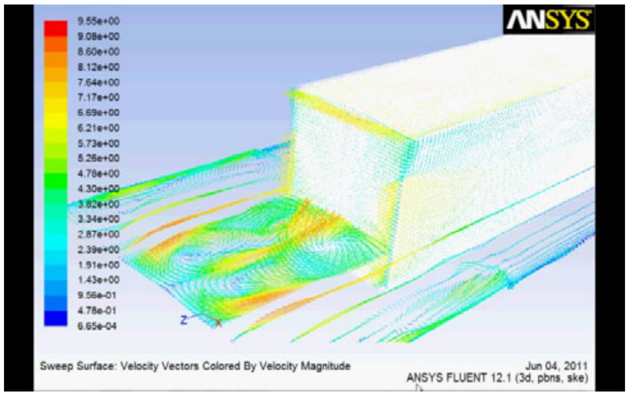


Fig. 2 Snapshot of ANSYS simulation to find the wind speed

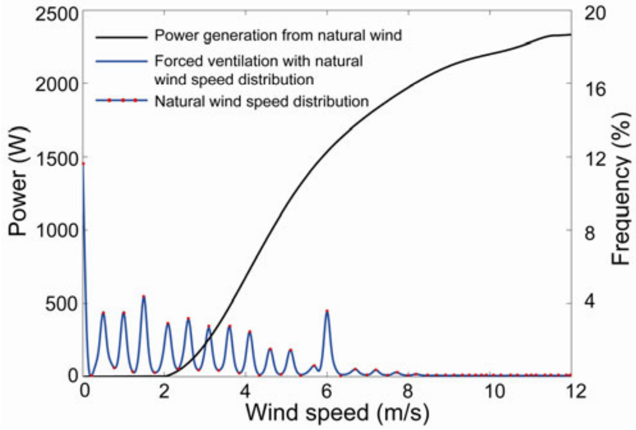


Fig. 3 Wind speed frequency distribution for natural and forced ventilated wind speed. Wind speed at location of the wind turbine versus the frequency (of occurrence of wind). The power curve for a 2kW VAWT is plotted against the wind speed. The peak at a wind speed of 6 m/s is due to the forced ventilation

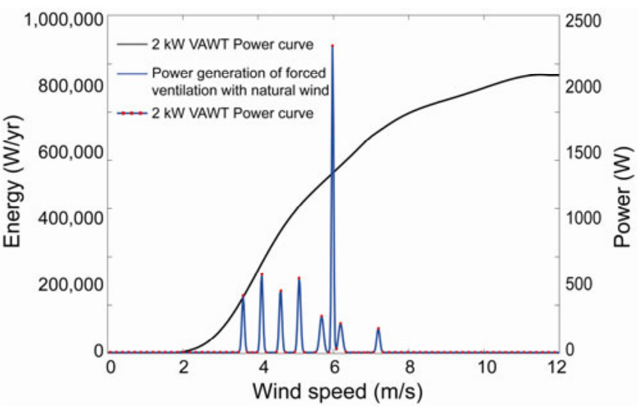


Fig. 4 Wind power generation from 2kW VAWT for various wind speeds. Wind speed versus energy (Watts per year) that can be generated with a 2kW VAWT. The peak at 6 m/s wind speed is due to the wind draft

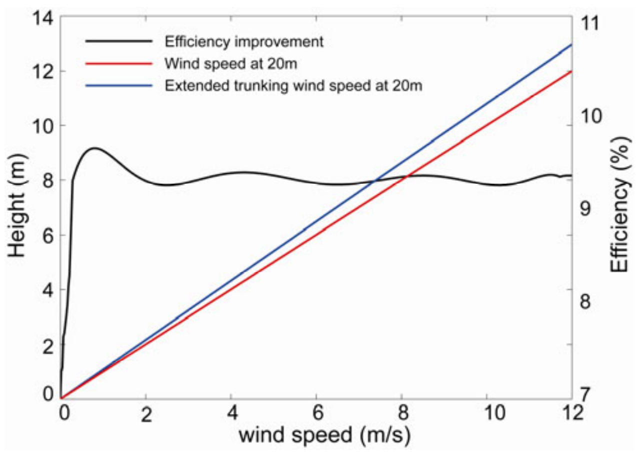


Fig. 5 Comparison of the wind profile at a height of 15 meters and 20 meters due to the wind draft generated due to the kinematic movement of the train. The red and blue lines show the variation of wind speeds versus the height at which the turbine is installed and efficiency. Efficiency improvement is depicted by the green solid line

causes the irregularity in speed and direction of the wind. There are undisturbed layers of the air as there is an increase in the altitude; the wind is no longer influenced by the surface characteristics. This phenomenon is known as vertical wind shear.

Figure 5 shows the comparison of the wind profile at 15meters and 20 meters. The MRT train tracks are built at a height of 15 meters. The height of the wind turbine can be increased by integrating the hydraulic lift in the main body of the wind turbine. It has already been proven that the wind speed and altitude are in direct proportion to each other and hence there is practical importance in harvesting more power from wind at greater heights. As can be seen from the figure, there is a 0.2% improvement in the efficiency in power generation from wind energy for the height of 20 meters.

4. Conclusion

The innovative approach to implement the VAWT is beneficial in reducing the dependence on non-renewable sources of energy and thus reducing the carbon footprint. In this study, we evaluated the use of VAWT in the environment of Singapore MRT system. The results from the simulations by CFD analysis showed that sufficient wind speed is induced due to kinematic movement of trains. This source of wind energy can be used to harness power.

The ideal location of the VAWTs would be in the vicinity of the stations, but still not very near so as to capture the diminishing strength in the wind speed as the train approaches the station due to deceleration. Since the power generated from wind increases with height at which the turbines are installed, integrating a hydraulic lift in the main body of the turbine increases the efficiency of harvesting the wind energy. This specification of the turbines can be used to the maximum during the non-operating hours of train services.

Based on the simulation, the energy that can be harvested from wind using a 2kW vertical axis wind turbine is 600,000 W/year. With a 5 meter increase in the height of the turbine, the efficiency of power generation increases by 0.2 percent. The execution of this idea requires minimal change in the infrastructure of the rail systems in Singapore and is non-invasive.

Progressively accurate simulations can be performed to generate precise models for the wind profile by taking into account the geography of the surrounding areas. The turbulence at the front face of the MRT trains will adversely affect the power generation from the wind turbines, further research can be made to find the optimum distance of the wind turbines from the approaching trains so that the effects of the turbulence is minimal and the efficiency further increases.

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