Breezing By:

Harvesting Energy in Low Wind Speed Conditions

2016-2017

0. Table of Contents

1. Introduction

Ever increasing worldwide demand for energy and ongoing depletion of conventional energy sources predominantly from fossil fuel has made it clear that the current scenario of global economy cannot be sustained indefinitely. Several sustainable alternative energy sources have been the topics of past and ongoing extensive investigations, e.g., wind, solar, hydro, wave power, geothermal, etc. (Center for Sustainable Systems, 2013). Compared to conventional energy generation methods, these techniques use resources that are inexhaustible and have little or no negative environmental effects. Although there are many possibilities of providing clean energy, several concerns such as, space, location, availability of technology, efficiency, etc. restrict its widespread application.

Wind energy systems have been in existence for over couple of millennia, dating back to ancient Persia when vertical axis windmill was invented to grind grain (Shen and Meisen, 2012). Since the ancient times, wind turbine has evolved significantly and is now one of the most popular techniques for producing clean and effective way of producing energy. However, these systems also encounter problems related to implementation, namely, size of turbine blades, overall structure size and consumer cost per kilowatt hour, safety, low frequency noise produced, etc. Despite these shortcomings, wind energy is unique in that it is prevalent and growing. If an effective method to harvest energy from low wind speeds were to be constructed, small scale wind energy harvesting could be applied to areas of high electricity demands or need to increase usage of clean, alternative energy.

This project is about small-scale generation of electric energy using small ducted wind turbines in areas where wind speeds are too low for conventional wind energy systems and where overall size and cost are also important factors. This system can be used in conjunction with other renewable source like solar energy. Such a system is well-suited for small households in remote areas of developing countries which are not connected to the utility grid due to economics and other reasons. Furthermore, the proposed system can be built in segments and easily deployed to these remote areas. Maintenance cost is also lower since there are no moving parts mounted on roof-tops or tall towers.

Figure 1: 3.45MW HAWT (Vestas, 2016)

2. Research

Wind energy or wind power is generated by converting wind kinetic energy to electricity using a combination of wind turbine and generator. Amount of power generated is determined by the speed at which the winds turn the generator. The amount of power harnessed is a cubed function of wind speed (i.e., doubling the wind speed increases power eight times). Wind speeds of 6-7 m/s are economically ideal for conventional wind power generation.

2.1 Different Wind Turbines: Wind turbines can be categorized into two major groupings based on the way the turbine spins:

(1) *Horizontal Axis Wind Turbine* (HAWT):

In HAWT, the turbine blades rotate along a horizontal axis that is parallel to the direction of the wind. These turbines are typically used at a large scale, in onshore and offshore wind farms, since their design is capable of utilizing large amounts of wind in open spaces, provided it comes

Figure 2: Different versions of Darrieus Vertical Axis Wind Turbine

from the correct direction. In order to ensure that HAWT faces the oncoming winds, a yaw mechanism is utilized in conjunction with a wind vane to sense wind direction (Shen and Meisen, 2012). A typical HAWT is shown in Figure 1. Increasing rotor diameter and wind speeds result in increasing power output of HAWT. Hence, these turbines tend to have large blades which need to be mounted on very tall, strong towers and hence are very expensive.

(2) *Vertical Axis Wind Turbine* (VAWT):
In VAWT, the blades rotate along a vertical axis which is perpendicular to the airflow and hence can operate with wind coming from all directions. In contrast to HAWTs, VAWTs offer a smaller footprint in that the turbine itself produces less noise, does not interfere nearly as much with the environment, and require fewer components. Some examples of VAWTs are depicted in Figure 2 (Shen and Meisen, 2012). Commercially made small scale VAWTs are popular for residential use. Most turbines typically generate 1 kW to 6 kW of power with a single unit.

(3) *Shrouded Wind Turbines*:
This is a HAWT that is much smaller than the conventional HAWTs described above and hence can be employed for residential use due to its low cost and footprint. This FloDesign Wind turbine is based on technology developed for jet engines which utilizes the wind energy that is lost around blades by surrounding the turbine blades with a shroud as shown in Figure 3 (Bullis, 2008). The shroud helps increase turbine speed, which increases power production.

Figure 3: FloDesign Shrouded HAWT

All the turbine designs described above, for a fixed can increase the power generation if turbine speed is increased which is only possible if they are placed in high wind speed areas. Hence, this limits their use in low wind speed areas where winds are below their cut-in speeds of 3-5 m/s. However, Venturi Effect from fluid mechanics can be employed to increase wind speeds by using a constricting mechanism, such as a conical shape, to increase the velocity of a fluid entering at its wider end. This concept can potentially be key to creating efficient small scale wind turbines, where low speed air in areas of need can be converted to higher speeds through a constriction to increase power output. This can overcome the limitations of size, location, wind speeds, and cost related to conventional wind turbines

2.2 Venturi Effect: The Venturi tube, or a constriction tube, is used in various applications where increased fluid velocity or decreased pressure is desired. The basis for the Venturi effect is derived from the Bernoulli's principle which state that a region of fast flowing fluid exerts lower pressure on it surrounding than a region of slow flowing fluid (Venturi, 2016).

$$\frac{energy}{volume} = P + \frac{1}{2}\rho v^2 + \rho g h$$

where, P is the pressure at the location of interest represented as force per area or energy per volume, ρ is the mass density, v is the flow velocity, g is the gravitational constant, and h is the altitude. The second term in the equation represents kinetic energy of the fluid and the third one represents its potential energy. According to conservation of energy the above energy density is constant, so that for two different regions in the flow,

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2$$

This implies that for two regions at the same height (h_1=h_2), an increase in flow velocity in one region corresponds to a decrease in pressure in order to keep the equation balanced.

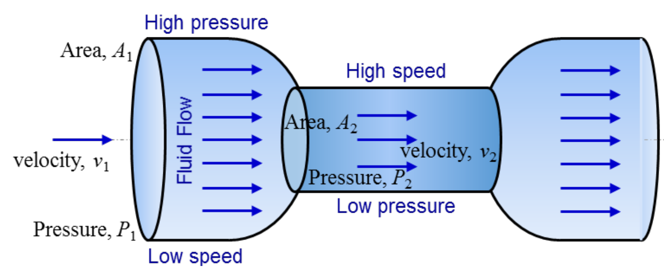

Figure 4: A Venturi Tube

In Venturi effect, the fluid flows through a constriction, where its molecules speed up in order for the total flow rate to remain the same at the inlet and the outlet. Since the molecules flow faster in the constriction, Bernoulli's principle indicates that the pressure in the constriction should be lower than it is outside (Halliday and Resnick, 1986). Figure 4 depicts a venturi tube with its different parameters. Based on the Bernoulli's equation given above, the theoretical pressure drop at the constriction is given by:

$$P_1 - P_2 = \frac{\rho}{2}(v_2^2 - v_1^2)$$

The volumetric flow rate for the Venturi is given by,

$$Q = v_1 A_1 = v_2 A_2$$

Combining the last two equations results in,

$$Q = A_1 \sqrt{\frac{2}{\rho} \frac{(P_1 - P_2)}{\left(\frac{A_1}{A_2}\right)^2 - 1}} = A_2 \sqrt{\frac{2}{\rho} \frac{(P_1 - P_2)}{1 - \left(\frac{A_2}{A_1}\right)^2}}$$

In this project, Venturi effect will be employed to increase wind speeds so that wind energy generation can be used in areas with very low wind speeds. In order to maximize wind capture at the inlet, wind catchers have to be utilized. Furthermore, the wind catcher should be omnidirectional such that it can capture winds from any direction without the need for a yaw mechanism.

<u>2.3 The Wind Catcher (WindTower)</u>: Wind Catcher (*bād-gir*: *bād* "wind", *gir* "catcher") have been used for over millennia in Persian villages like Yazd which are located in arid climate (Dave, 2016) to create natural ventilation in buildings. Figure 5 depicts one such wind catcher structure from Yazd. The downward air flow captured through openings is used to cool the inside of the household.

Figure 5: Bād-gir (Wind Catcher) from Persia

In this project, four towers shown above will be combined into a single omnidirectional wind catcher which will be employed to maximize wind capture to be supplied at the inlet on the venturi system described earlier.

3. Engineering Goals

The main goal of this was to demonstrate that a venturi duct combined with an omnidirectional wind catcher can be used to create a small-scale wind turbine power generation system that can be used in areas where conventional wind turbines don't work due to low wind speeds.
The project goals were achieved specifically through the following:

- Using readily available parts, implement Venturi ducts of different sizes to determine its effectiveness in increasing wind velocity in the duct (see Figure 6).
- Based on the ancient *bād-gir* (wind catcher), design an omnidirectional wind catcher to capture winds from all directions and direct the flow into the venturi duct.

- Implement the complete electrical system comprising of turbine generator, load, as well as a controller to determine flow of energy to load and/or energy storage system.

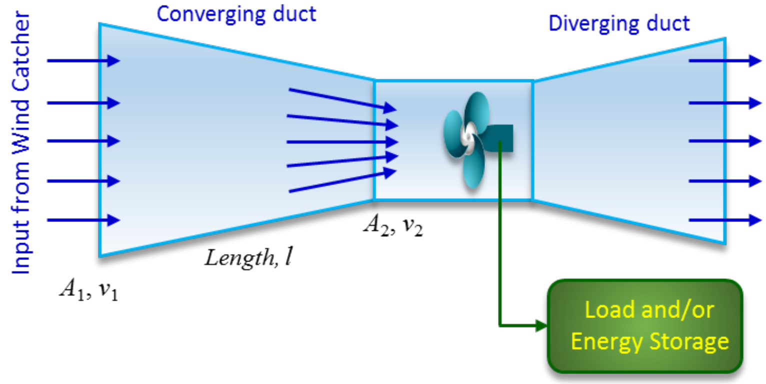

Figure 6: Conceptual depiction of Venturi Duct based Wind Power Generation

4. Materials

- Metal duct reducers: 10:8, 8:6, 6:4, 6:5, 5:4.   PVC pipe reducers: 4:3, 4:2
- 12V, 0.3A DC motor, 5cm (2”) and 7.6cm (3”) PC fan rotors (for turbine blades)
- Handheld anemometer (HoldPeak HP-866B)
- Electrical components:
  - Arduino UNO microcontroller board
  - Components for battery charging system: Voltage sensors: 12kΩ (×2), 2kΩ (×2), 10Ω (×2), 100pF (×2), [1]MOSFETs TK33S10N1ZLQTR-ND with gate drivers TLP250 (×2)
  - Energy storage device: Ultra-capacitor or 12V rechargeable battery
  - Solderless breadboard, soldering iron, jumper wires
- Testing and Characterization:
  - 0-20V, at least 5A DC power supply (Agilent E3633A), multimeter,
  - Variable speed window and 20cm PC fans to generate different input wind speeds

[1] These parts are salvaged from earlier projects just to build a test prototype. Exact parts suitable for system specification can be replaced here.

5. Procedure

6.1 Preliminary Simulations: Before implementing the idea, it was decided to thoroughly simulate the venturi duct by varying different dimensions to determine the factors that determine velocity increase. Simulations were done using *ANSYS* modeling software, *Fluent* (Ansys, 2016). Computational fluid dynamics simulations are conducted in ANSYS using the basic process involving creation of geometry, meshing, and solutions. Simulation results are provided in section 7. Based on these results different venturi ducts were designed, built, and characterized.

6.2 Venturi Duct Design

1. Connect different diameter duct reducers to create Venturi ducts with different inlet to outlet size ratios: 10:3, 10:2, 8:3, and 8:2. The final narrow duct should be long enough to do wind speed measurements and also to place a turbine. For wind speed measurements cut a slit in the duct near the outlet end and place the anemometer in the direction of the air flow. A completed Venturi duct with anemometer is shown in Figure 7.

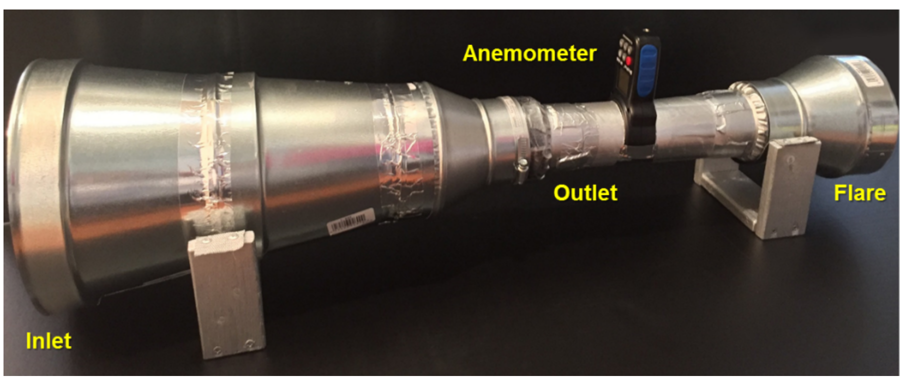

Figure 7: Venturi duct with anemometer

2. Use a DC motor (as a generator) and a salvaged computer fan with the same diameter as the Venturi outlet) to create a scaled wind turbine to test the system. A Ducted turbine assembly attached to the Venturi duct is shown in Figure 8.

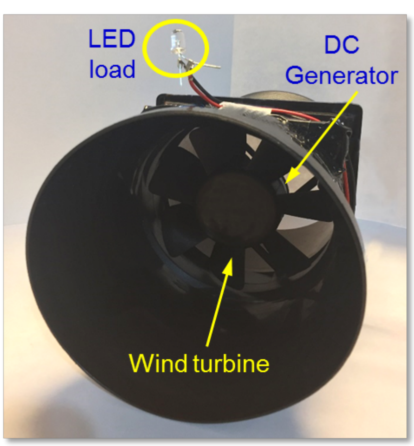

Figure 8: Ducted turbine assembly

6.3 Wind Catcher Design

1. Similar to the bād-gir shown in Figure 5, create a wind catcher that can capture maximum amount of wind from all directions and funnel it in to the Venturi duct inlet.

2. For the purpose of this scaled prototype, the diameter of this wind catcher should be such that it can be inserted in all the above Venturi ducts of sizes varying from 10:3 to 8:2.
3. Use four baffles cut out from rigid material to direct winds from directions in to the inlet.

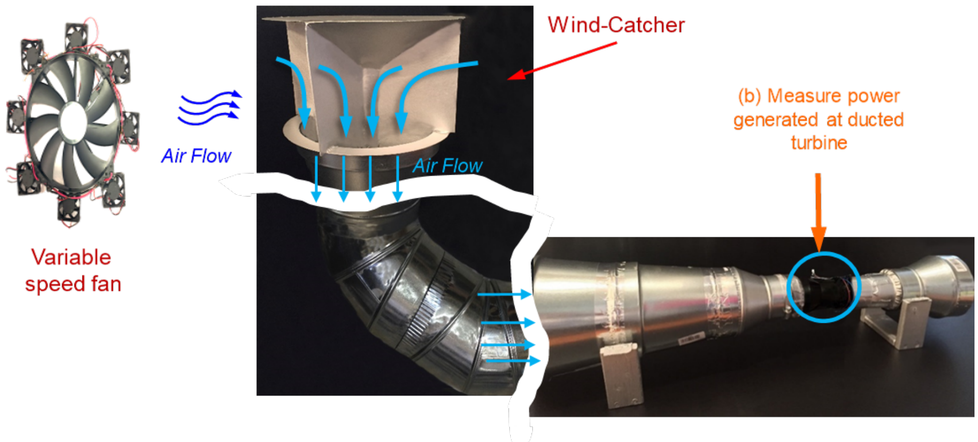

Figure 9: Wind catcher and Venturi based design

Attach this wind catcher to the Venturi duct inlet using a same diameter bent duct. The wind catcher implemented for this prototype is shown in Figure 9.

6.4 Testing and Characterization of the Wind Turbine System

1. <u>Wind speed measurements</u>: For all the Venturi ducts designed above measure outlet wind speeds for different inlet speeds created using a variable speed.

2. <u>Power measurements</u>: Connect the turbine assembly to the Venturi duct. Connect the outputs of the DC generator to an LED as electric load and connect two multimeters to measure current and voltage generated. Repeat the power measurement when the turbine is placed near the inlet (i.e., as a traditional wind turbine). This will help determine the gain in power generation due to the Venturi duct.

6.5 Energy Storage Control System

1. Any renewable energy source may not be used in a standalone manner to directly supply the load. For example, when there are no winds or wind speeds are too low, the load may still need to be supplied with electric energy. For such scenarios, there should be an energy storage system that works in conjunction with the wind energy generation system.
2. Build a scaled demonstration prototype charging system which is conceptually depicted in Figure 10. This system is based on solar battery charging concepts described in (Deba 2014).

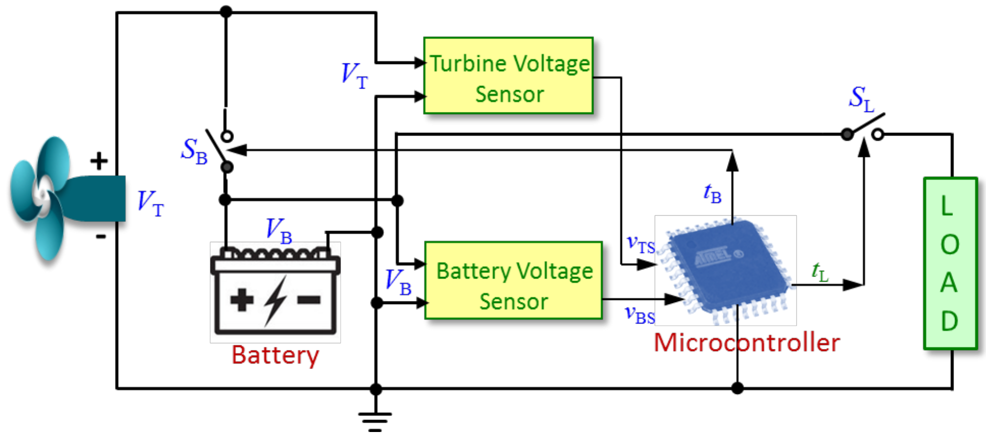

Figure 10: Closed-loop system for controlling flow of energy to load and energy storage

3. In this diagram the rechargeable battery (or other storage device) is connected to the renewable source through a controlled switch S_B. The load is supplied by the battery through another switch S_L. These switches are controlled by the Arduino microcontroller using a preliminary charging control algorithm given below. Resistive potential dividers are used as voltage sensors to sense the turbine (V_T) and battery (V_B) voltages used in the algorithm. The corresponding sensed output voltages, v_{TS} and v_{BS} are supplied to the microcontroller to control the above switches. Once the battery is fully charged (V_{FULL}), it is disconnected from the source and is reconnected only when it is near the discharged limit (V_{LOW}). Note, the upper and lower thresholds for charge control (V_{FULL} and V_{LOW}) are determined by the rechargeable battery characteristics. Other option not pursued here is to connect in such a way that load can be supplied by the source as well as the battery depending upon the availability.

   The charge and load controllers loops through the following algorithm:

   if ($V_T \geq V_B$) and ($V_B \leq V_{LOW}$)

   then { charge the battery and connect the load by making t_B = t_L = "1"

   continue charging the battery until ($V_B \geq V_{FULL}$) }

   else { disconnect the battery from turbine by making t_B = "0"

   keep the load connected to the battery until $V_B \leq V_{LOW}$

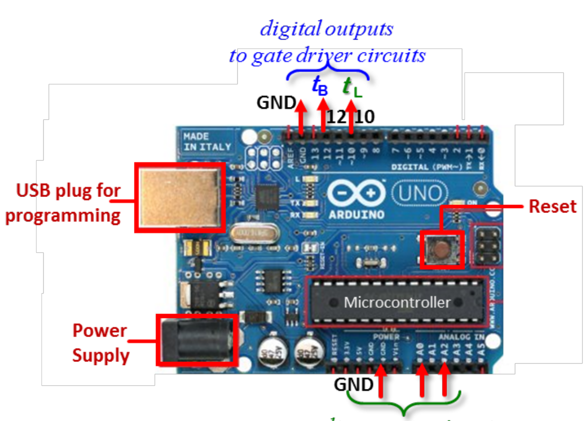

Figure 11: Microcontroller connections

The detailed schematic diagrams for the control system is presented in Figure 12. Based on the sensed turbine and battery voltages (v_{TS} and v_{BS}) and the above algorithm, the controller will produce digital signals t_B and t_L which are then amplified by the driver circuit and

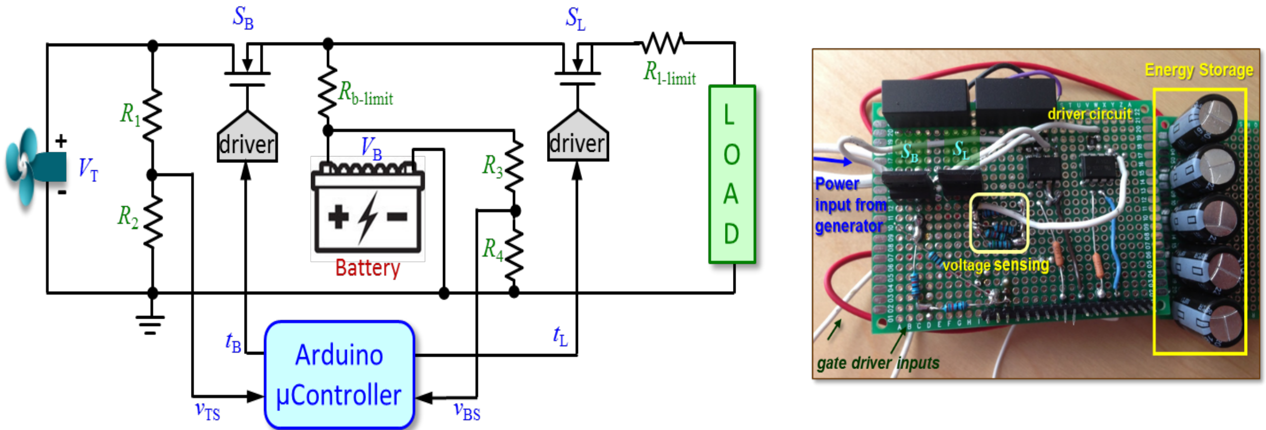

Figure 12: Schematic diagram and implementation for the load/storage control system

supplied to the gate inputs of the corresponding switches, S_B and S_L. These switches connect or disconnect the storage device (battery or supercap) and the load to the turbine generator. The driver circuits are needed since the microcontroller digital outputs are not strong enough and may not have voltage levels needed for controlling the power MOSFETs that are used as switches.

4. The energy storage system is controlled using the Arduino microcontroller. The interconnections between the microcontroller and the energy storage system are shown in Figure 11. Other safety and protection mechanisms can also be built into this system. For example, if there voltage surge at the turbine, the load and energy storage system can be disconnected by the microcontroller. The above system can be modified and used in conjunction with additional renewable energy sources.

6. Results and Discussion

Simulation Results for Venturi Duct

Figures 13-14 give plots for simulations conducted to determine the effect on outlet wind velocity when different dimensions of the Venturi duct were changed. Simulations assumed ideal conditions with uniform air flow at every point in the inlet, no turbulences, and no presence of rotating wind turbine inside the constriction. These simulations were done to determine the main design parameters.

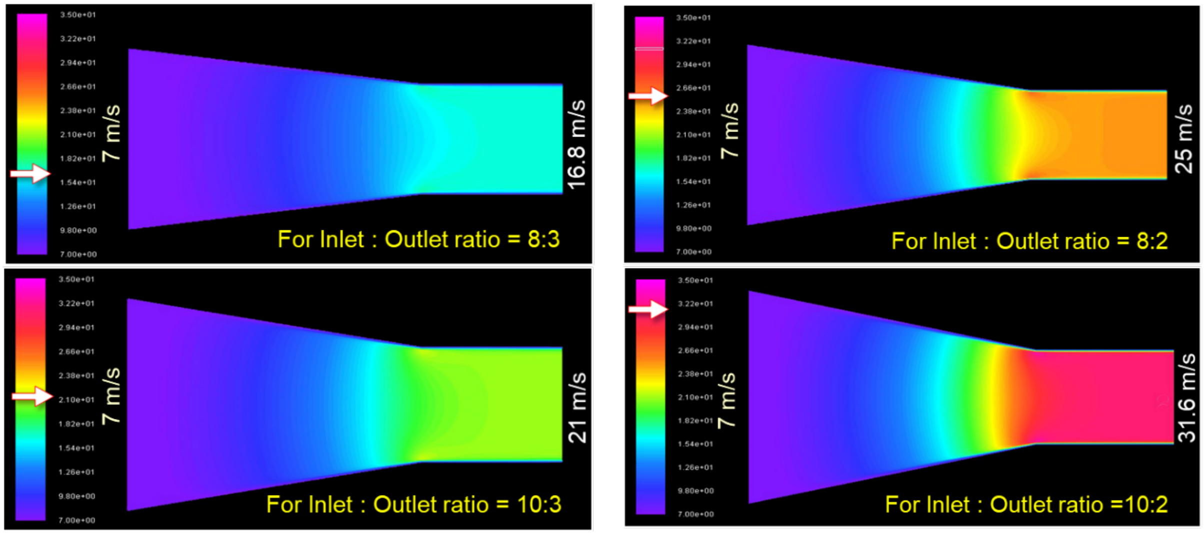

Figure 13: Effect of varying Venturi duct inlet:outlet area ratios on outlet wind velocity for inlet velocity of 7 m/s

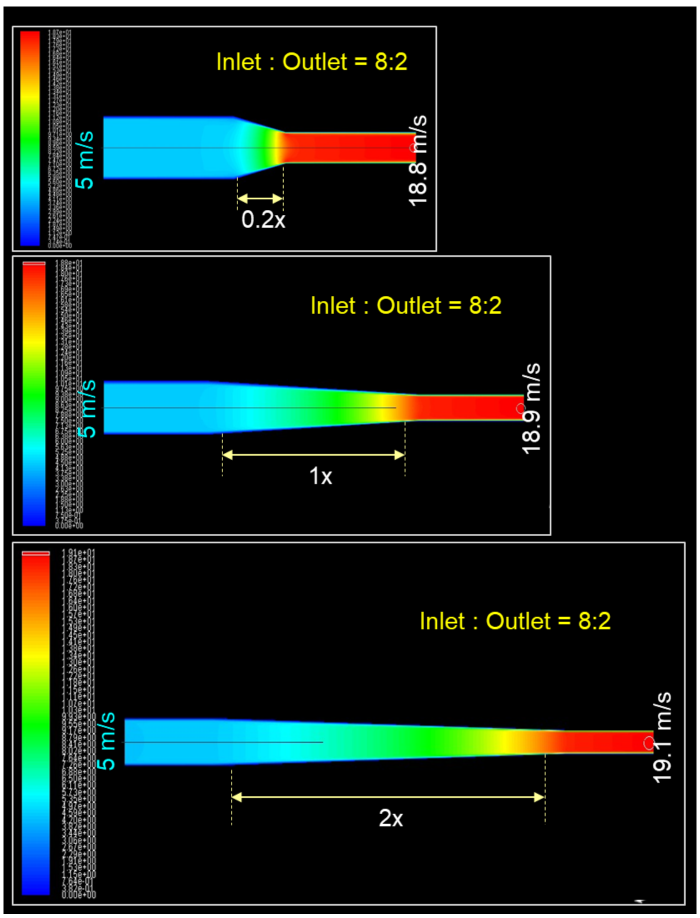

Figure 14: Effect of varying Venturi duct length on outlet wind velocity for inlet:outlet ratio=8:2, inlet velocity=5m/s

From the above simulations it can be seen that when the inlet to outlet area ratio was changed there was significant change in the output wind velocity. However, when the Venturi duct length was change there was hardly any change in the outlet wind velocity. Hence, subsequent experimentation was done with variations in inlet and outlet areas.

Figures 15-16 give the test and characterization data measured for different wind-catcher based Venturi duct designs. Figure 17 gives comparisons from the point of view of gain in wind velocity.

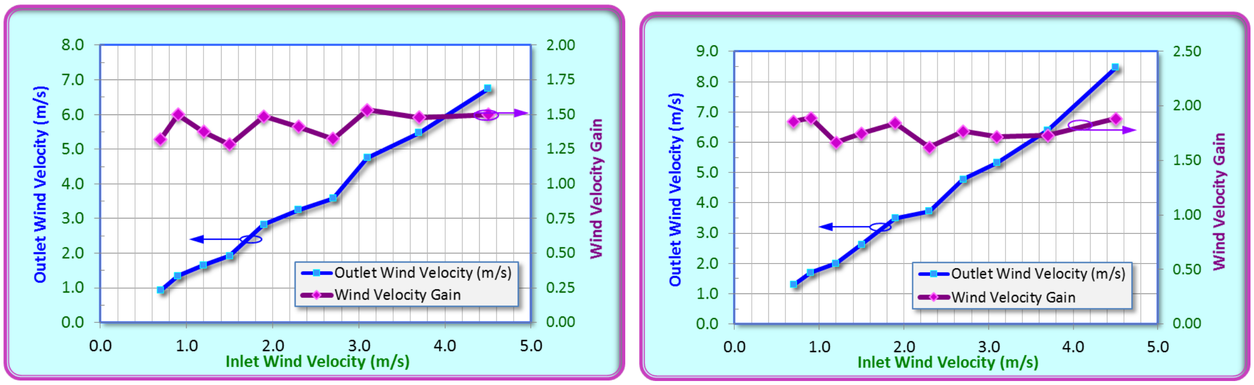

Figure 15: Outlet wind velocity measurements for inlet:outlet diameter ratios of 8:3 and 10:3, respectively

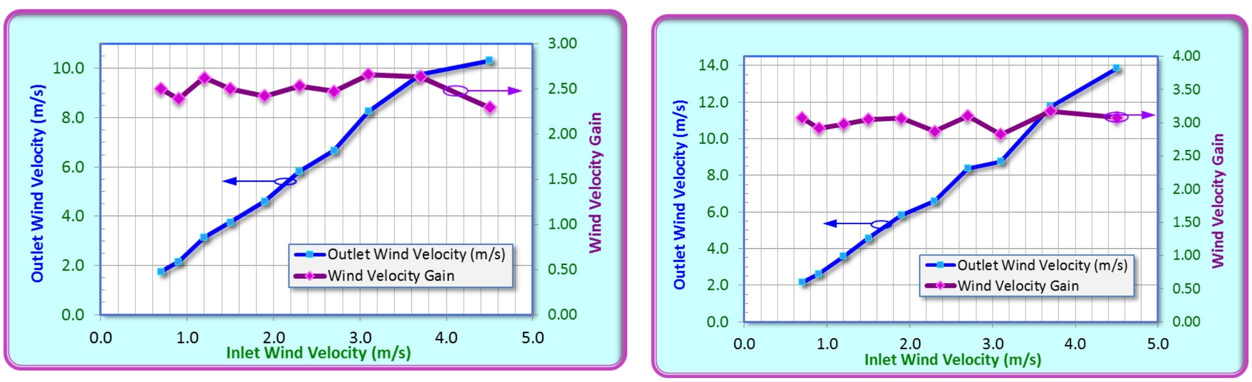

Figure 16: Outlet wind velocity measurements for inlet:outlet diameter ratio of 8:2 and 10:2, respectively

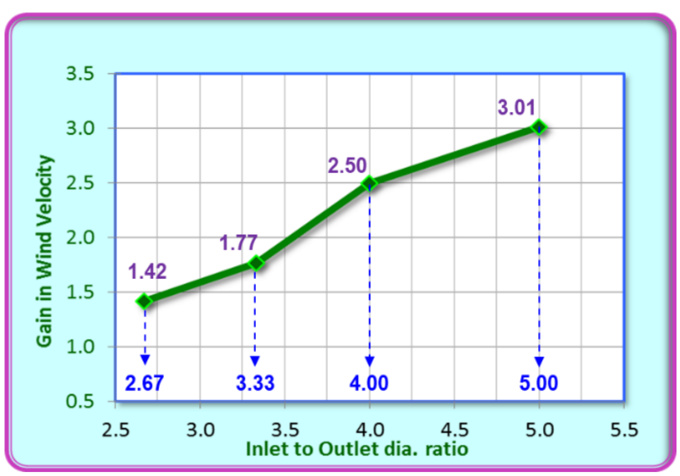

Figure 17: Gain in wind velocity for different inlet:outlet ratios for the Venturi duct

Hence, as the *inlet:outlet* size ratio for the Venturi duct increased, the wind velocity also increased proportionately. For the ratios of 8:3 to 10:2 the average gains in wind velocity were 1.42 to 3.01. That is, if the traditional turbines that need wind velocities above 3m/s are used in the presented system, then they can now run at wind velocities below 3m/s.

Figure 18 gives results of the power generated when the prototype wind turbine with generator was placed at the inlet of the Venturi duct and inside the duct at the outlet of the constriction. From Figure 18, it can be seen that as the wind velocity increases, power generated increase rapidly (faster than quadratically). For the tested wind power generation system with inlet:outlet ratio of 10:3, the average increase in power generation using the proposed method was 2.57.

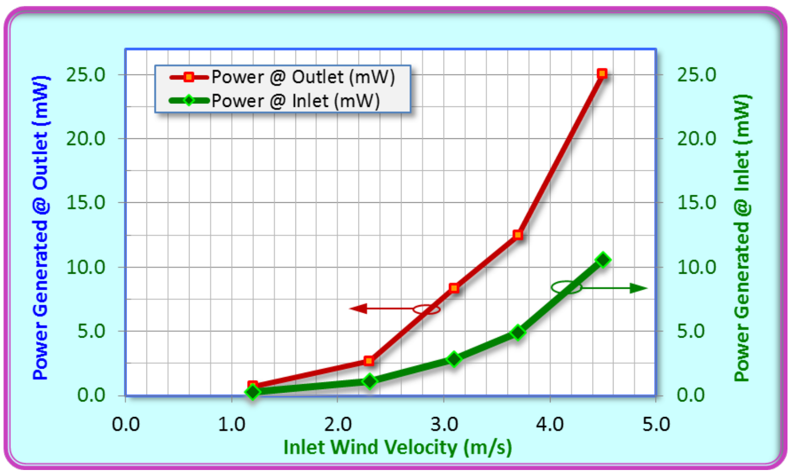

Figure 18: Power generated for a 10:3 Venturi duct for different inlet wind velocities

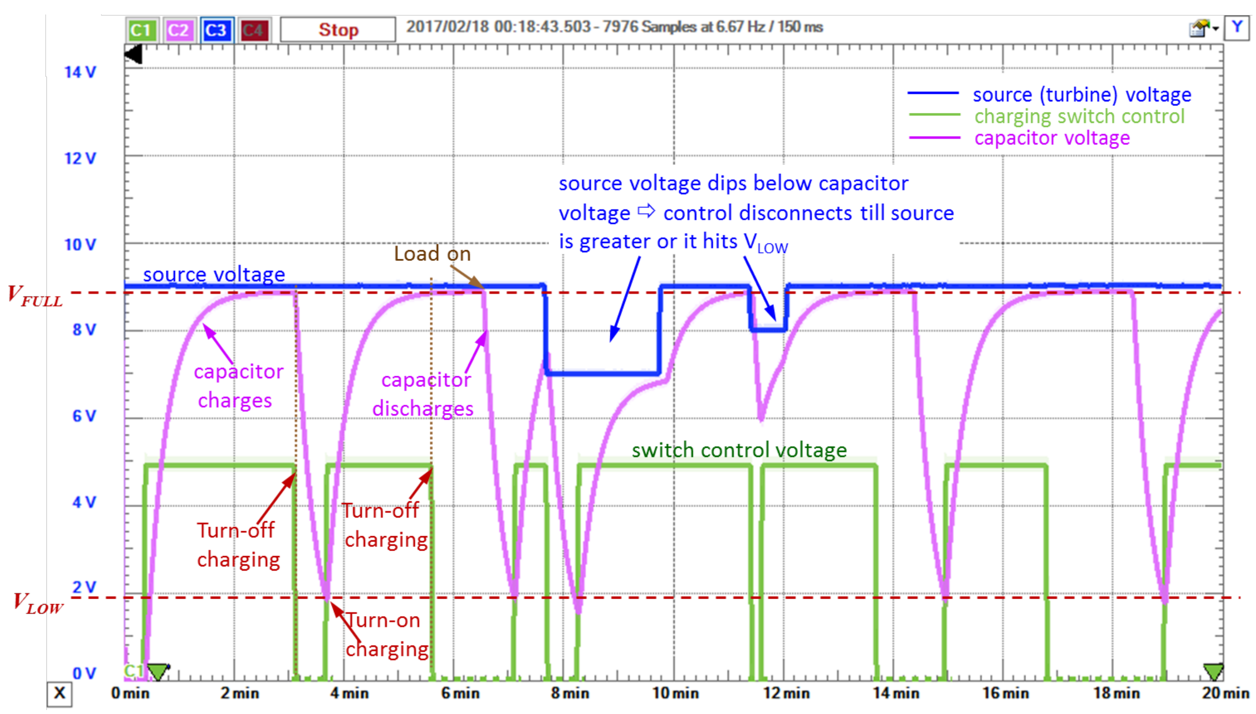

Figure 19: Waveforms showing the functioning of the energy storage and load control system

Figure 19 shows the waveform demonstrating the functioning of the control system for the flow of energy from the turbine generator (source) to energy storage (a capacitor in this demonstration) and load. It charges the battery (capacitor in this case to capture measurement results over a short period of time compared to actual battery) whenever the battery voltage is below the low threshold (V_{LOW}) and stops charging when it is fully charged (at V_{FULL}).

Venturi ducted wind energy harvesting system presented here can extend the use of wind as a renewable energy source even when wind speeds are below 3-5m/s. The structural design, implementation, and maintenance costs are lower compared to traditional wind turbines since there are no moving parts mounted on roof-tops or tall towers. This also minimizes or eliminates hazards to birds. The segmented design structure is cheaper to make, transport, and maintain because in case of damage or failure only the corresponding segment / component need to be replaced. The energy storage and corresponding control system, if properly designed can provide round the clock electricity to the household, especially if it can combined with other renewable sources.

7. Conclusions and Future Work

The main engineering goal of this project was to demonstrate that wind energy can be generated in locations where wind speeds are lower than the typical cut-in speeds of traditional wind turbines. This was achieved by designing a ducted system comprising of a Venturi duct and an omnidirectional wind catcher. An energy storage system prototype controllable by an Arduino microcontroller was also implemented but can be extended to add features like, overcharge protection, short circuit, and overload protection, etc. Based on the test and characterization data presented in section 7, a wind energy system is plausible in areas with low wind speed if Venturi ducted wind turbines are used along with an omnidirectional wind catcher. Figures 17-20 indicate increase in wind velocity by factor of 1.42 to 3.01. For a 10:2 Venturi ducted turbine, the corresponding increase in power generation capability is 2.57. Because of the non-linear relationship between wind velocity and power generated (Figure 20), when wind velocity doubles, the power produced increase by a factor of 4-8.

The scaled prototype presented here provides enough evidence to build an experimental full-scale design. Based on the published data from a developing nation (Jhunjunwala *et* al., 2016) a large portion of households have no electricity and quite far from the nearest utility grid. Significant improvement in quality of life can be achieved for a typical, small household in these remote areas if there is enough electric energy for couple of LED lights, a fan, small TV, phone, and small cooler. Based on the data given, (Jhunjunwala *et* al., 2016) this results in a total daily energy usage of less than 1 kWh. This energy requirement can be satisfied using a 300-400W turbine. Alternatively, a smaller turbine can be used if the presented system can be complemented by a solar cell energy system.

A traditional 300-400W ducted turbine can be built with a rotor diameter of about 1m. A quick online search resulted in a cost of less than $400 for this wind turbine generator (Lombardo, 2015). The cost is even lower if these are purchase in bulk quantities. Based on the gain in wind velocity data presented here (Figure 17), the inlet of the Venturi duct should be around 5m. The rest of the system for wind catcher can be built as an architectural element by the household and its outlet can serve the purpose of providing ventilation also. The wind catcher window areas should be made as large as structurally possible and stable because larger these window area the more wind it can capture. If each household's energy requirement goes down a bit, then slightly larger system can be built and shared among few households to provide a more cost effective solution. See Figures 20 for suggested use of the proposed system.

Lastly, there is a need to design and implement a better controller for flow of energy to battery and the load. The circuit should work in tune with the charging characteristics of the battery, e.g., temperature sensing, preventing deep discharge which could damage the battery, load current sensing, etc. It should also include various protection mechanisms like, overcharge protection, short circuit and overload protection, etc. Add a voltage regulator before the battery charger in order to limit the output voltage to the value required by the battery.

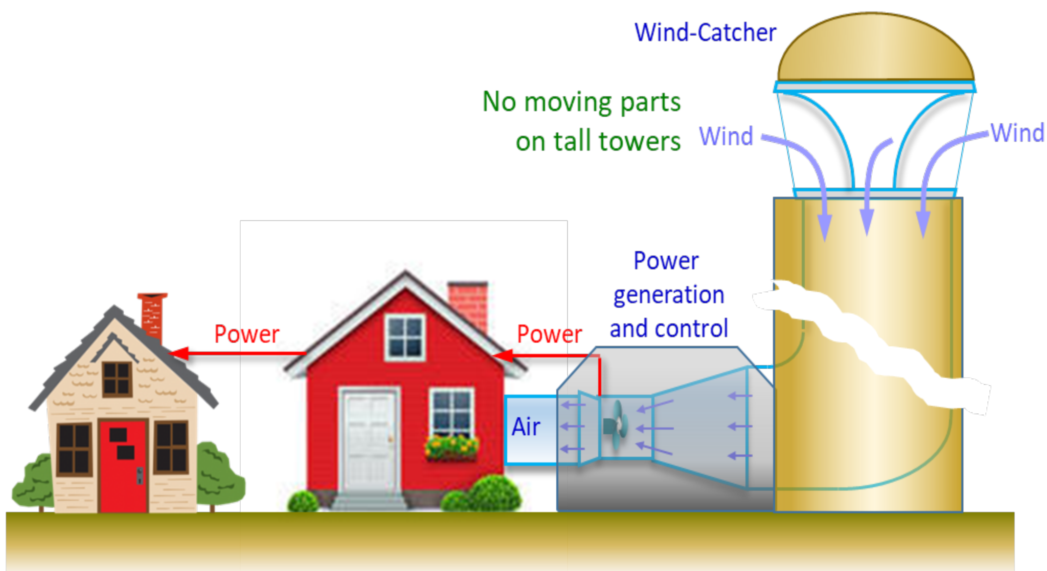

Figure 20: Suggested use of the Venturi ducted wind energy system

8. Statement of Outside Assistance

This project and research was done entirely at home without outside assistance other than parent supervision in necessary situations.

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