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Sponsored Project Titled

"WIND DRIVEN AIR STORAGE SYSTEM"

Performance Analysis Report

Submitted to

NATIONAL INSTITUTE OF WIND ENERGY

(NIWE)

By

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KCG COLLEGE OF TECHNOLOGY

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Table of Content

1. Introduction to Design

The system comprising of three blade wind turbine was designed as per the specifications,

- Wind Turbine: 5 kW (Class III)
- Single Stage Oil Lubricated Piston Displacement Air Compressor: 5 HP
- Storage Cylinders for Compressed Air: 9755 Litres
- Hub Height: 20 m
- Rotor Diameter: 4 m
- Type of the Tower: Lattice

The rotor shaft of the wind turbine is connected to piston displacement oil lubricated air compressor of 5 HP capacity. The nacelle is equipped with a rotating union which couples the rotating compressor to the hose mounted at height of 17.39 m. The compressed air is stored within the tower to avoid additional space. The tank is designed to store 9755 liter capacity of air. Pressure regulating valves are provided at the outlet of bottom cylinder to meet the load demands.

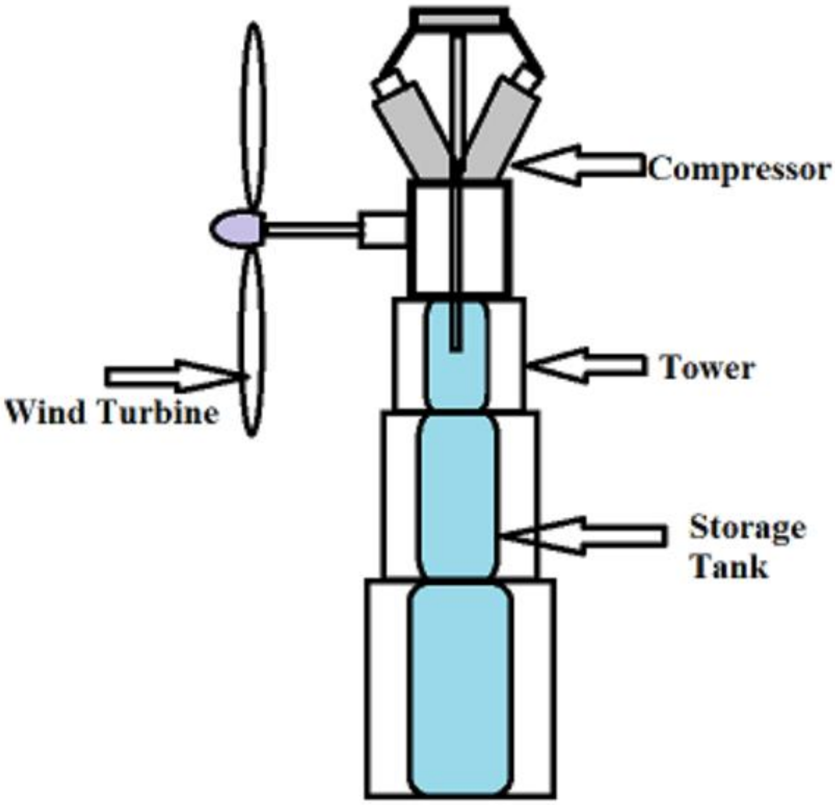

Fig 1: *Schematic Diagram of Proposed System*

a. Installation

The Designed turbine was installed on top of 19 meter lattice tower with storage cylinders embedded within the tower structure, as shown in Fig 1, this while erecting was found to have maintenance implications and hence the tower foot extension structure was designed as shown in Fig 2, is used to enhance the operation and maintenance of the storage cylinder.

Fig 2 : *Tower Foot Extension structure fixed over the foundation.*

The rest of the tower components were mounted above the Tower foot extension and the whole process were reported in the previous report.

For operation and maintenance, ladder structure was designed and implemented on the tower structure to reach up to the top level, along with fencing for the safety as shown in fig 3, in addition to it a platform and pulley structure was commissioned at the top portion to enable ease of operation and maintenance as in fig 4.

Fig 3: *Ladder and Fencing*

Fig 4: *Platform and Pulley for maintenance*

b. Data Monitoring

The various parameters that are required the monitor the performance of the designed wind turbine are as follows:

1. Wind speed
2. Wind Direction
3. Vibration in the structure
4. Temperature built up in the cylinder
5. Pressure built up in reservoir

The designed turbine and blades were tested with compressor at both low and high wind prone zones. The test results were satisfactory and submitted in the earlier reports.

2. Analysis and Validation of Various Design (PMC – requirement)

a. Structural analysis of the entire system under extreme wind speed of the site.

b. Dynamic Analysis
c. Possibility of having pressure regulators, NRV for each cylinder
d. Weight Comparison of electrical generator and compressor of same capacity
e. Theoretical calculation for the design to verify proper functioning of the system.
f. Study of temperature built up.
g. Starting capability of wind turbine at various back pressures.

The above requirements were analyzed and validated results were submitted in the previous report.

3. Mechanism employed to enhance the operation of system

a. Automatic Pressure release system

This system was designed to eliminate the back pressure exerted on the compressor due to compressed air stored in the tank, in this system an additional reservoir of 15 liters was used as intermediary storage before the actual storage tank, and this is connected to the compressor with a rotating union and NRV, which allows flow of compressed air in to the reservoir, in addition the reservoir is equipped with electronically controlled solenoid valve to release the compressed air in the reservoir immediately after the wind turbine stops it rotation due to low/no wind. Thereby maintaining the backend of compressor at zero bar during every start of rotation of wind turbine after the wind speed resumes operating level. This prevents the stalling of wind turbine to some extent.

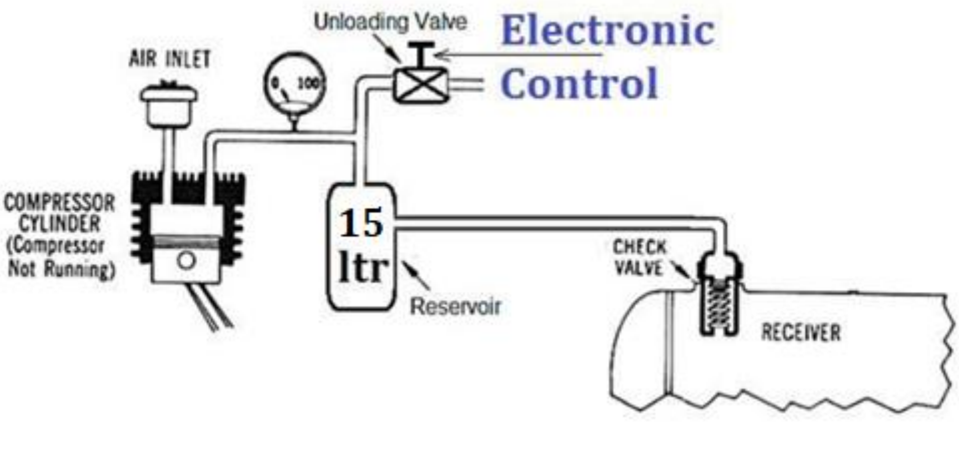

Fig 5: *Automatic pressure release system*

The operation of electronic solenoid to release the pressure is controlled by a relay which is triggered by a control system as and when the turbine stops rotation by precisely monitoring the rotation of turbine.

The system was tested at the lab and was implemented and demonstrated during the PMC visit.

b. Automatic Braking System

In addition to the manual braking system with brake drum and brake pads, that can be applied by pulling the brake wire from the bottom of the tower, an automatic braking system is also designed and implemented with the following components.

1. Anemometer
2. Solenoid valve
3. Electronic control system

   The anemometer continuously monitors the wind speed, this signal from anemometer is converted into electrical signal and fed into the control system. This signal is compared with the reference signal corresponding to wind speed of 15m/s. (since the whole wind turbine driven compressor was designed to operate till a maximum operating wind speed of 15 m/s, this was derived after considering the operating environment and safety factor in small wind turbines)

Fig 6: *Anemometer extended from the main tower*

Once the wind speed exceeds 15m/s a relay is triggered to excite the solenoid connected immediately after the rotating union after the compressor. This solenoid valve that is configured in NO mode, will close thereby shutting down the compressor with back pressure, thereby bringing the wind turbine to stall and preventing the system from any damage due to high wind speed. This control system will continuously monitor the wind speed and will reopen the solenoid valve once the wind speed falls below 15m/s only after a fixed time delay to prevent sudden shunting of turbine and blades during drastic wind fluctuations.

c. Parallel Storage and Delivery system

The storage tanks were initially connected in series with NRV fitted at the beginning of the tanks and put into operation for a period of 15 days.

During this period the overall pressure achieved in the tanks were found to reach a maximum of only 2.5 bar.

And at the same time was found to reach different pressures when the tanks were individually connected to compressor as shown in the table.

Tank	Volume	Pressure achieved
Lower	6000 Litres	3 bar
Middle	3000 Litres	5.1 bar
Top	755 Litres	7.8 bar

Table 1: *Pressure obtained in each cylinder*

From the experimental data of the above table, it was decided to connect the tanks in parallel configuration with individual NRVs and control valves, there by opening and closing of both inlet and outlet of each tanks can be controlled independent of other tanks, this enables to store compressed air at different pressures in different tanks thereby achieving maximum utilization.

Block diagram of PIPO

d. Weather Monitoring system

The weather monitoring system comprises of the following sensors:

1. **Anemometer** – to measure wind speed – it's a 3-armed cup rotor type with a

measuring range of 2 – 50 m/s with high accuracy and 10 impulse / RPM. Its input for the open collector type NPN is 12v to 30v DC, and output is 40 mA. It works on the principle of optoelectronic sensor pickup action.

The sensor used is an industry standard unit. This was mounted at hub height about 2 metres alongside the wind turbine perpendicular to the wind axis.

2. **Vibration of tower segment** – Piezoelectric sensor which generates an electrical charge in response to mechanical stress or vibration, When the crystal is subjected to mechanical vibration, it generates a small electrical charge, which can be measured by a connected circuit or device. The electrical charge is proportional to the magnitude of the vibration. They can detect mechanical faults or abnormalities, such as imbalance, misalignment, or bearing wear, before they cause serious damage or failure. Here in our system it is fixed to the vertical member of the top segment in the tower immediately below the compressor.
3. **Temperature of tank** - measured with K type thermocouple, that can measure the temperature in the range of -20 to 135°C, it measures the surface temperature, the thermocouple probe is placed in contact with the surface being measured. The heat from the surface is transferred to the thermocouple junction, generating a voltage that is proportional to the temperature difference between the junctions, Overall, the K-type thermocouple is a reliable and accurate method for measuring surface temperature. Its simplicity and versatility make it an essential tool in a range of industries, including manufacturing, engineering, and research.
4. **Wind Direction - Rotary Pot**

   Wind direction is an important parameter to consider in various applications, such as weather monitoring, wind energy production, and navigation. One way to measure wind direction is by using a rotary potentiometer or rotary pot. To measure wind direction, a rotary pot is mounted on a horizontal axis, and a vane or wind sock is attached to the axis perpendicular to the direction of the wind. As the wind blows, the vane or wind sock rotates the axis, which in turn rotates the wiper arm of the rotary pot. The position of the wiper arm corresponds to the angle of the wind direction, it includes integrated Hall elements and digital signal processing. The angular position information is provided by a magnet integrated with the sensor’s shaft. The sensor provides a pulse width modulated signal. Most models are designed to operate from either a 5Vdc regulated or 9-30Vdc unregulated supply, with a high stability circuit and EMC immunity to 100V/m.

The electrical signal generated by the rotary pot is typically read by a microcontroller or data acquisition system, which converts the signal into a digital value that can be displayed or analyzed. The digital value is often mapped to the corresponding wind direction using a lookup table or mathematical function.

5. **Pressure transducer** – pressure transmitter is integrated with high-precision diffused silicon pressure core, the internal special integrated circuit converts the sensor millivolt signal into a standard current signal, which can be directly connected with the computer interface card, control instrument, intelligent instrument or PLC, and the current output mode can be used for remote transmission. this is a small size, light weight, all stainless-steel sealed structure transmitter, which can be used in corrosive environment. The product has extremely high vibration and impact resistance and easily to install, it can measure pressure up to a maximum of 10 bar and it is used to monitor the pressure achieved in the reservoir.

e. Data Logger

A data logger, also known as a data acquisition (DAQ) system, is an electronic device used to collect and record data from various sensors and instruments over time. It typically consists of three main components: sensors or instruments, a data logger unit, and a computer or software for data analysis.

To power the data logger unit, that requires a 24V DC power supply, a step-down transformer is often used to convert the 230V AC power supply to the required 24V AC supply. This transformer reduces the voltage and provides isolation from the main power supply, helping to protect the data logger unit from power surges and other electrical disturbances.

Then a rectifier is used to convert the 24V AC supply to a 24V DC supply that can be used to power the data logger unit. This DC voltage is then smoothed and regulated to ensure a constant voltage supply to the data logger unit.

The data logger unit itself typically consists of a microcontroller, memory for data storage, and analog-to-digital converters (ADC) for converting the sensor signals into digital data that can be stored and analyzed. The data logger unit may also include communication interfaces, such as USB or Ethernet, to transfer the collected data to a computer or other device for further analysis.

Data loggers are used in a variety of applications, such as environmental monitoring, industrial automation, and scientific research. They allow for continuous monitoring and recording of data from multiple sensors over time, providing valuable insights into changes and trends in the measured variables. With advances in technology, data loggers have become more compact, reliable, and capable of handling larger amounts of data, making them an important tool for many industries and fields.

The sensors were calibrated with secondary standard and connected to Data Acquisition card for collection of data at control desk through Modbus Protocol.
The User interface in the PC is used for data logging the sensor data, the frequency of storing can be programmed and for this monitoring system , the interval of sampling is set at 2 minutes. The data can be viewed graphically as well as exported to Excel for further analysis.

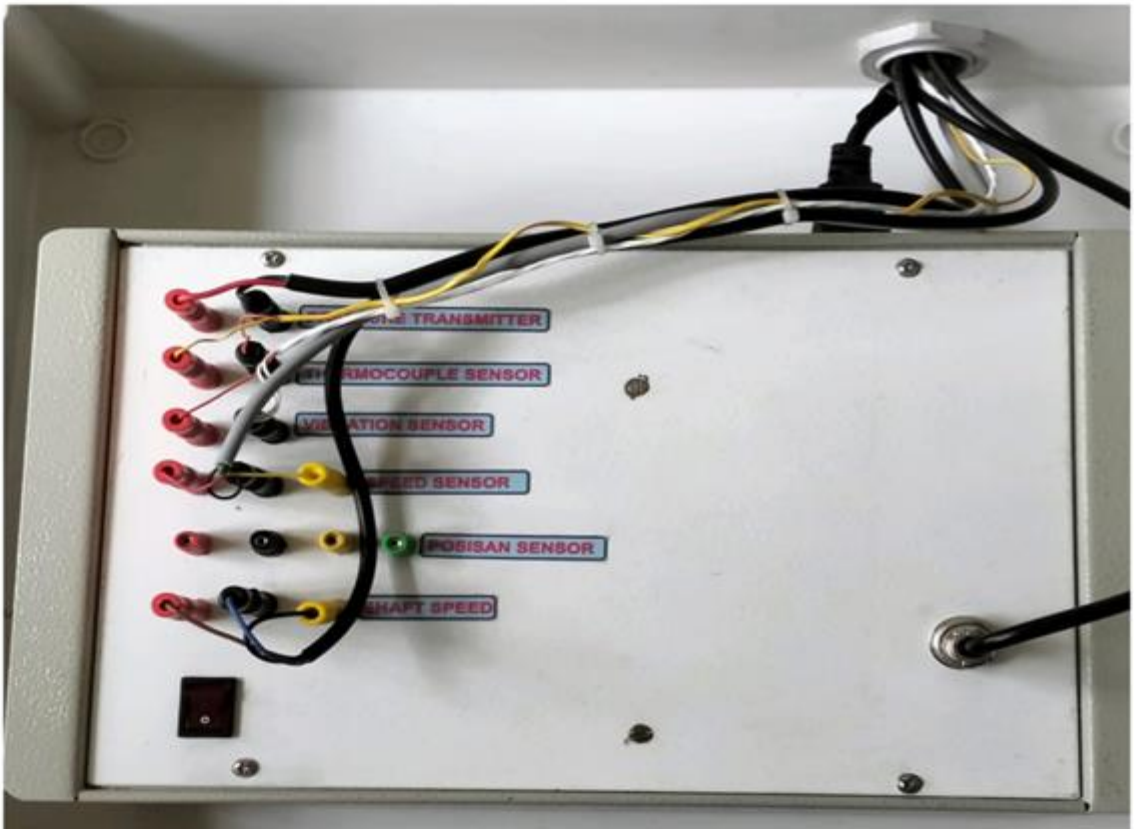

Fig 7 : *Data Acquisition box with IP 65 Enclosure fitted at the top section below compressor.*

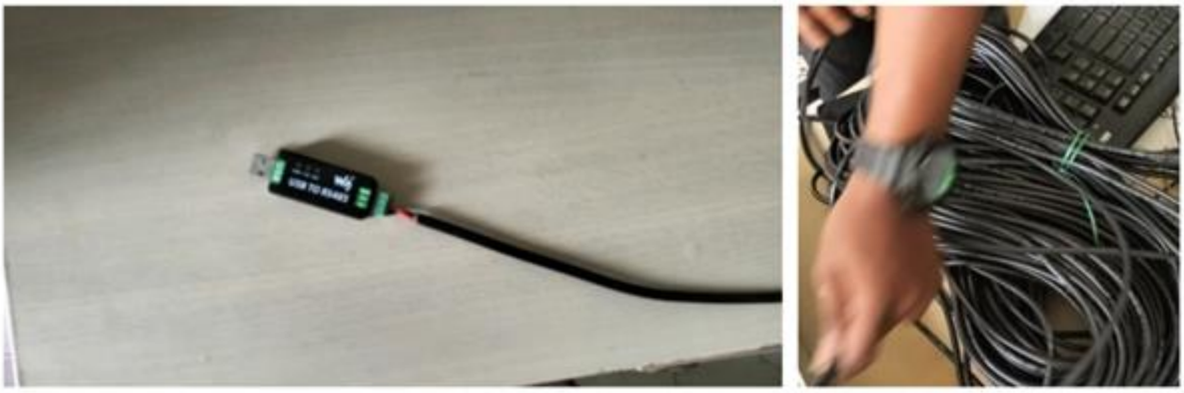

Fig 8: *Modbus Connector and Cable*

The top segment of tower houses a IP65 control box, that holds the DAQ card, the power conditioning systems for the sensors, the electronic control system of automatic braking, and automatic pressure release system.

4. Performance monitoring system

The performance of the wind turbine was monitored for a period of roughly six months, since August 2022, with all the systems in place, A sample set of data recorded from the monitoring system is shown below.

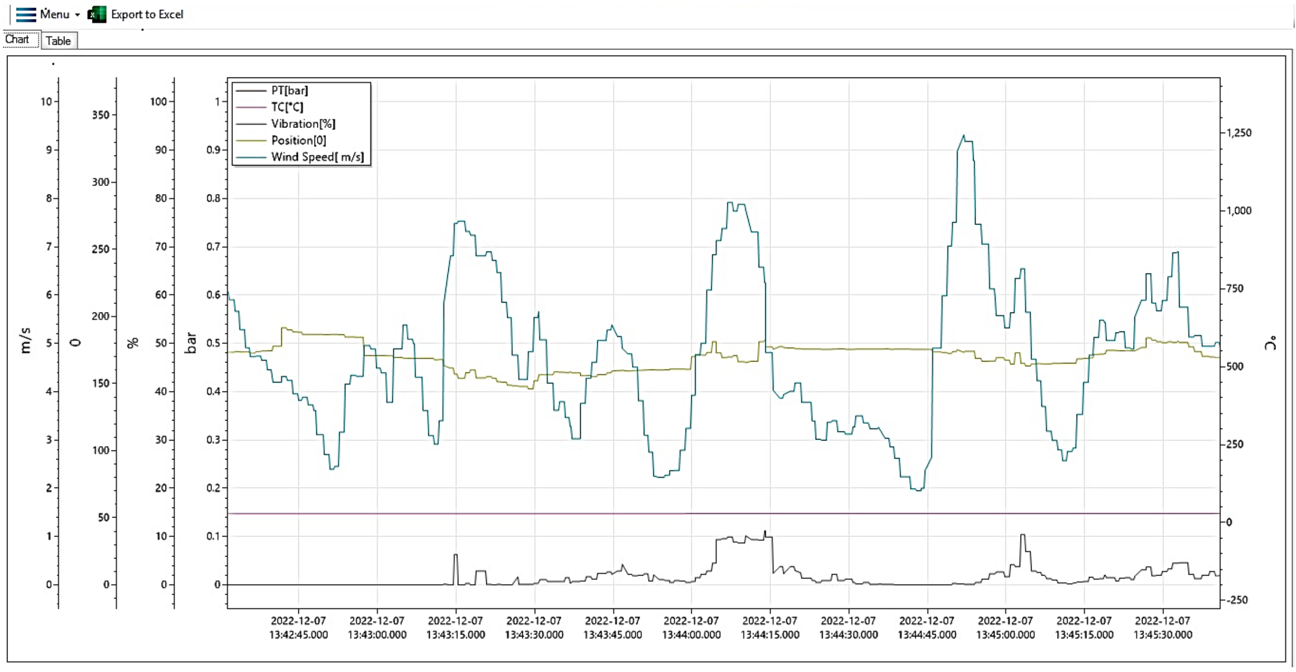

Fig 9: *Recorder data displayed in graphical format*

From the recorded data it was found that the compressor was able to compress air and store in the cylinder.

5. Performance Analysis of Compressor

The performance of the turbine and compressor was observed under different conditions as described.

a. With series connection of tanks

The 3 tanks were connected in series with NRV at the input section of all the tanks. the data collected from various sensors are shown here with graphical representation.

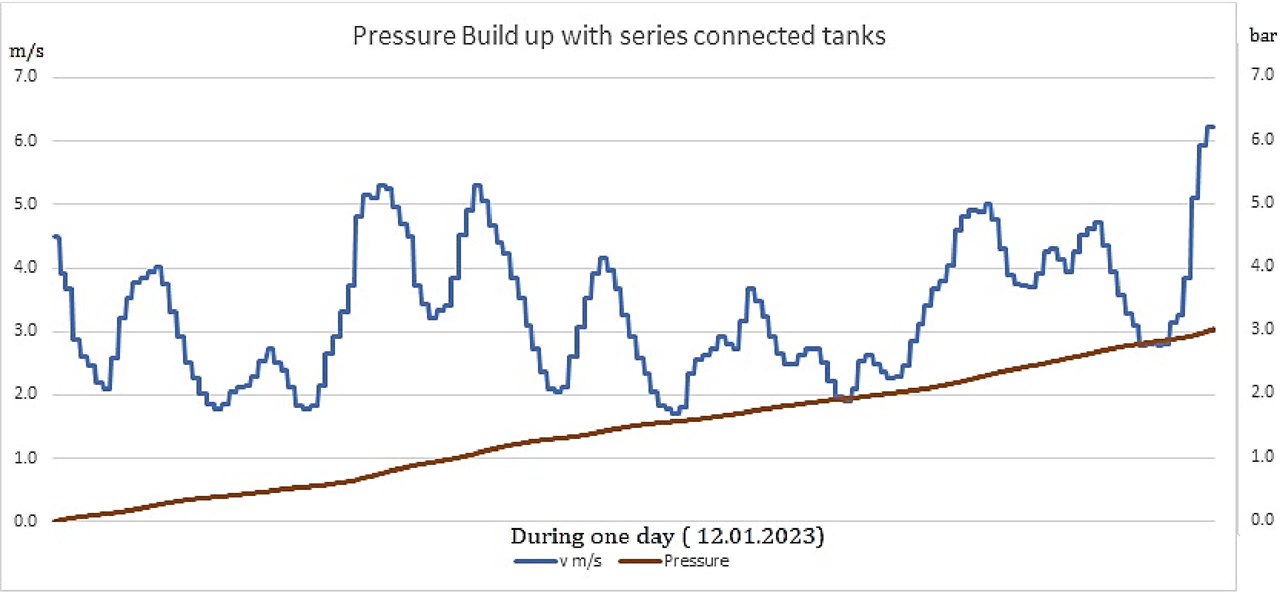

Fig 10: *Pressure Buildup over time on a particular day.*

b. Report

From the table the tanks with capacity of 9755 liters can store compressed air at a maximum pressure of 3.0 bar, this is not sufficient to drive any useful load like that of pressure wash/Aero generator etc., hence connection of tanks in series is not a feasible method for effective usage of available wind power.

c. With parallel connections of tanks

The 3 tanks were connected to the output of compressor, in parallel with individual NRVs at the input section of all the tanks as shown in fig X. this system was put in use and data was collected for a period of roughly 3 months since the data collected from various sensors are shown here with graphical representation.

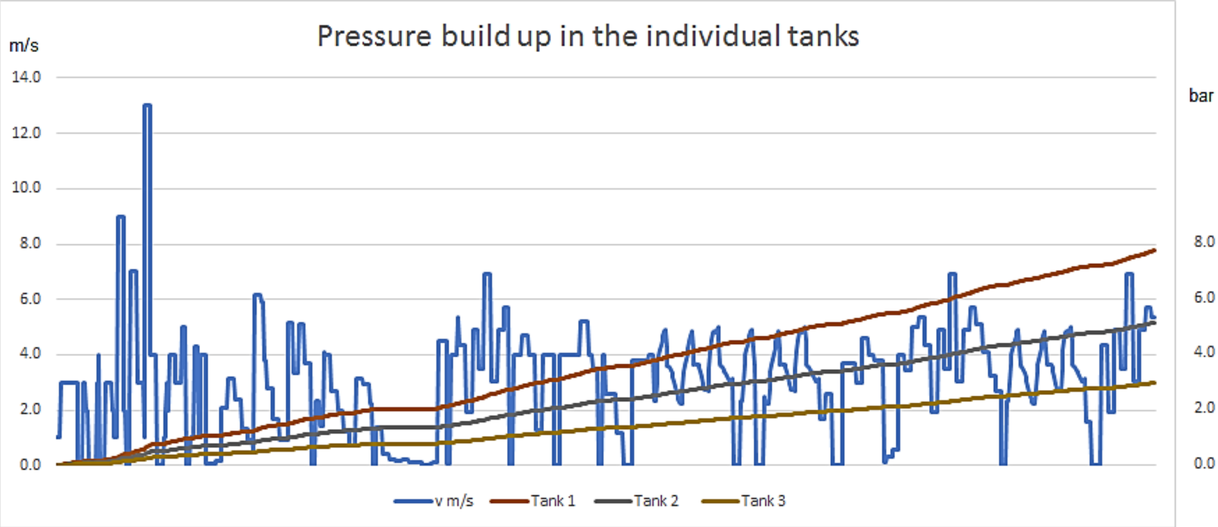

Fig 11: *Pressure Buildup over time on a particular day.*

d. Report

From the data recorded in the table below, it clearly shows that the wind driven compressor was able to store the tanks with different capacity at a different maximum pressure in them, the reasons may be due to back pressures exerted by them to the compressor.

Tank	Volume	Pressure achieved
Lower	6000 Litres	3 bar
Middle	3000 Litres	5.1 bar
Top	755 Litres	7.8 bar

The opening and closing of the inlet of various tanks were operated manually after monitoring the pressure in the cylinders.

The outputs were also tapped from the three cylinders at different pressures for the different applications.

e. Measurement conditions

The region under test falls in the low wind regime and the wind turbine was designed to produce power at 3 m/s, reaching the rated power at 10 m/s and stopping power production at 15 m/s by stalling the braking system. The average wind vector (speed and direction) at 20 m above the ground level for the location is measured every minute in the weather monitoring station, from the data, the wind speed ranges from 4 to 6 m/s during the period of measurement (from 12th August to 28th February 2023). The wind speed in this duration is considered for the optimum operation of the wind turbine. The minimum and maximum annual wind speeds in this duration are 1.3 m/s and 8.67 m/s, respectively, whereas the average wind speed is 3.83 m/s.

f. Data processing

The primary data was binned and averaged over different time blocks ranging from 5 seconds to 1 minute. This was to allow for delays in the response of the turbine due to the difference in inertia between itself and the anemometer. After examination, the data set using 30 second blocks was selected as the best option for further processing.

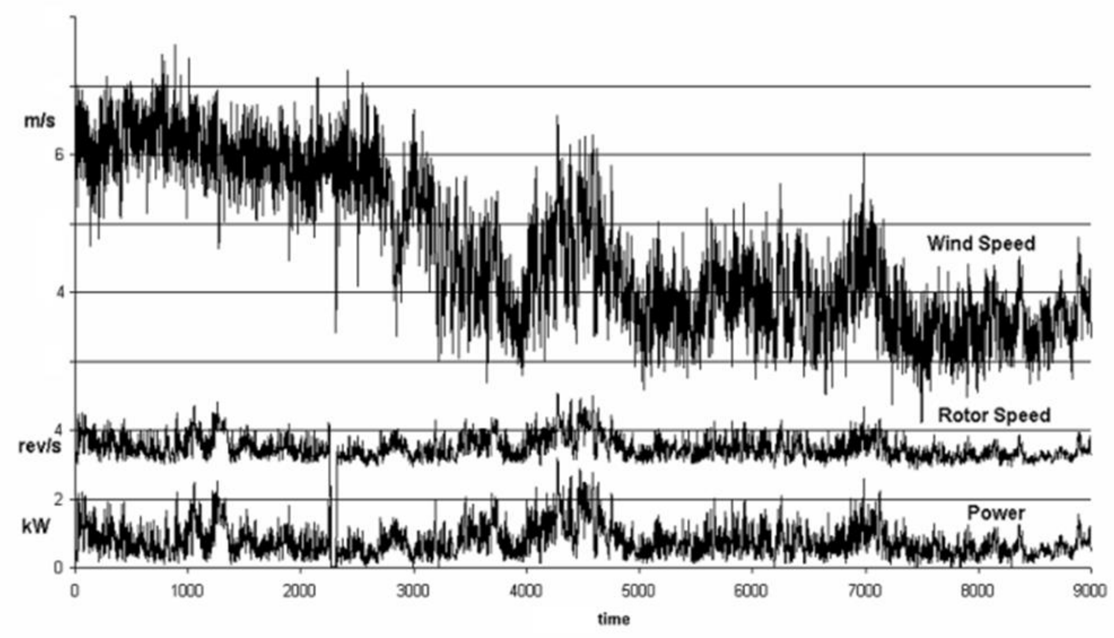

Fig 12 : *Overview of the entire test*

Figure 13 compares wind speed and rotor speed for the same duration. the graph clearly show that there is severe over-regulation at wind speeds above 10 m/s that does not allow the wind turbine to reach its maximum power potential and it never reaches the rated speed of 5 rev/s (300 rpm).

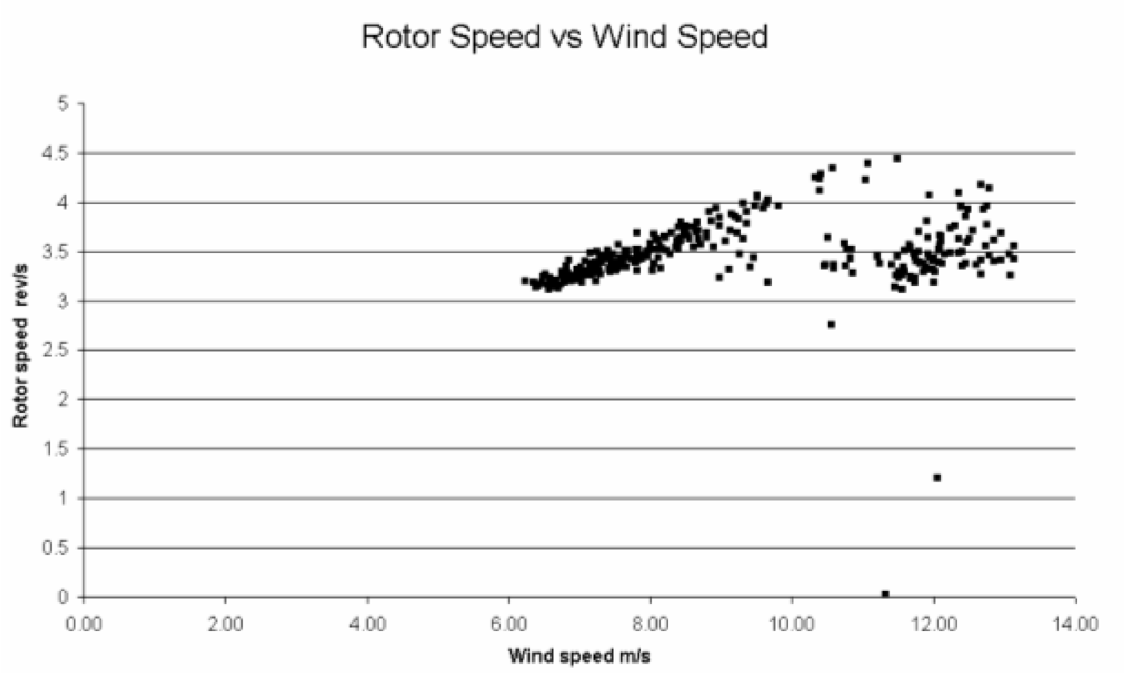

Fig 13: *Rotor speed and wind speed*

Above 10 m/s, where power regulation caused blade coning, the early data recorded was erratic and use of these figures would distort further data processing. A cut off point was set at 3500 seconds and the readings taken before this point were not used for the detailed calculations. As the wind speed during the day did not fall below 6 m/s, and regulation cut in at 10 m/s, the final results were based on a narrow band of rotor speeds between 3.1 and 4.4 rev/s

g. Field observations

The Proposed wind turbine driven compressor is designed robustly to survive hard conditions in turbulent zones on a relatively short mast which is much nearer to the ground than other designs. As a result, it will encounter gusts and rapid but small changes in wind direction that cause it to continually accelerate, decelerate and oscillate noticeably around its yaw axis. Rarely does it run at a steady speed pointing directly into the wind.

During the tests, it was noted that the anemometer reacted very quickly to wind changes and was direction independent. On the other hand, the much greater inertia of the wind turbine would cause a delay in response in rotation. The attitude of the blade angle due to rotation speed and direction of yaw means that the wind turbine will rarely instantaneously match the theoretical maximum power generation values under real operating conditions. This contrasts sharply with wind tunnel tests where yaw and shear winds are not an issue and the turbine has time to settle down in between changes in loads or wind speed to present a stable set of readings reflecting its optimum performance.

h. High-wind operation

It was thought that the blades designed for high wind operation would not create much of a difference compared to blades designed for low wind regime, but the tests have proved this to be incorrect. Wind speeds more than 10 m/s produced an erratic power output from the turbine, well above the rated values, in fact in a short duration of time of roughly 15 minutes during the cyclone, the compressor was able to store 7.5 bar of air in the top tank, this also proved that the turbine, compressor, tower structure was able to withstand the extreme conditions without major damage.

6. Conclusions

As shown in Figure 12 and 13, the d ratio than the other speed bands. Bearing in mind that these tests were performed on a wind turbine that was operating on par, the results seem to indicate that it is operating more efficiently in the middle speed speed range 3.5 to 4.0 rev/s produced a higher power coefficient at a higher tip speerange 3.5 to 4.0 rev/s.

The lower tank with a max pressure of 3 bar - was utilized for pressure wash of vehicles.
The middle tank with a max pressure of 5.1 bar – was tapped using the pressure regulator valve – and was utilized for pneumatic applications in SAE workshop for air filling and operating other pneumatic tools.
The top tank of 755 liters was able to store compressed air to a maximum pressure of 7.8 bar, the same was used to drive the Aero generator to generate power. It was found to drive the Aero generator can work safely in the range of min 3.4 bar to max of 15.1 bar.
This power generated is currently tested and used in an isolated mode.
In future this can be connected to grid on a regular basis to generate power once the tanks are filled with compressed air to the requisite operating level.

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8. Publications

Ammal Dhanalakshmi, M., Deivasundari, P. Modular compressed air energy storage system for 5kw wind turbine: A feasibility study. Clean Techn Environ Policy 23, 2201–2212 (2021). https://doi.org/10.1007/s10098-021-02127-7