Performance analysis of a hybrid vertical axis wind turbine through CFD for distributed generation in rural areas of Peru

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Abstract. Currently, in the developing countries of Latin America there is a great deficiency in the transmission of energy. In Peru, being a developing country, there are many rural areas and indigenous and peasant communities that do not yet have access to electricity due to the difficult access or cost of installing transmission lines in their location. Therefore, the present work will briefly evaluate the current situation of the country and, from that, will formulate a solution based on the development of distributed generation systems using small wind turbines. For this purpose, this paper will develop the preliminary performance analysis of a hybrid vertical axis wind turbine (VAWT) by using the computational fluid dynamics (CFD), for this, the data of the wind resource of Cajamarca, a province in Peru, will be used for this analysis because in this province there is a great wind resource. Even a short aerodynamic and efficiency study was carried out in order to characterize its behaviour with different air flows as they are found in many rural sectors of Peru.

1. Introduction

Currently, in the developing countries of Latin America there is a great deficiency in the implementation of distributed energy systems. In Peru, being a developing country, there are many rural areas and indigenous and peasant communities within the country that do not yet have access to electricity, mainly due to the difficult access or cost of installing transmission lines to their location. Besides, wind energy is one of the strongest and most profitable with advanced technological development. Current wind turbine designs are capable of generating electricity at a similar or even lower cost than traditional generation sources.

On the other hand, the variability of wind flow in a locality requires the use of measuring instruments to be able to characterize the son and obtain specific data, such as the prevailing wind direction, wind speed, atmospheric pressure, ambient temperature and relative humidity. This information will be useful for the correct design and implementation of wind generation systems following the corresponding technical standards. For this purpose, we will use the technical reports of the annual national energy resource issued by the corresponding entities, in the case of Peru they are the System Economic Operational Commission (COES), the Ministry of Energy and Mines (Minem), Osinergmin, among others. In addition, we will locate the regions that have wind power generation plants in the report and map of the National Interconnected Electric System (SEIN). It should be noted that according to reports from the National Environmental Information System (SINIA), they indicate
that some departments such as Amazonas and Loreto records that 24% of its population or has access to electricity, despite having a high wind energy resource within its territory that can reach an average of 5 Watts at a height of 10 meters [1].

Likewise, Peru has rural areas with great power for the installation of renewable energy, both solar and wind, throughout the national territory. We have chosen to choose Cajamarca as the place to study the wind resource from where we will obtain the necessary data for this analysis [2]. We will take the information of the monthly and annual speed regime, highlighting the months where we find its highest values. From these values we will be able to condition the study of CFD in a better way than just based on a single value, on the contrary we will analyze different values which will give us results of different powers, which will be used in a review and basis for future work. such as the implementation of farms and wind farms close to communities very isolated from the electricity grid and where it is not economically feasible to arrive by power lines.

2. Literature review

2.1. Available wind energy resource

As for the country's wind energy resource, according to the Osinergmin, only a minimum percentage of the resource is used [3]. Thus, the matrix is mainly oriented to two energy sources, these being hydroelectric and thermoelectric, which among them account for approximately 96% of the annual investment in recent years (see Fig. 1.a).

![Figure 1](image)

**Figure 1.** (a) Evolution of the energy matrix, (b) average annual wind speed at 10m. [1]

Therefore, using these distributed generation systems is essential for all rural communities to have access to electricity and thus take advantage of the generation distributed in the country, since it is currently not used for the most part (see Fig. 1.b).

2.2. Wind resource in Cajamarca

One of the areas with the highest power index per square meter (W/m²) in Peru is Cajarma, however some areas on the coast have much higher rates, but these areas are closer to the electricity grid and there is no access difficulty found in Cajamarca and other rural areas [2], [6]. For this reason, it is ideal that these towns with the greatest wind resource and close to communities be identified in order to encourage distributed generation projects such as solar or wind farms, which together with other energy sources can provide complete stability, avoiding the risks of electricity cut since
individually each renewable energy source is somewhat slightly insecure because there will not always be stability since they are part of nature. Below we show graphs (Figure 2 and Figure 3) of the wind resource that Cajamarca has, particularly areas of Santa Cruz and Chota.

Figure 2. Wind resource in each department of Peru and peak wind speed period in Cajamarca. [6]

Figure 3. Wind resource available at Cajamarca and nearby areas (Wind speed [m/s] and power density [W/m²]). [6]

In addition, the average speed in low areas that are close to localities and communities in months of high wind flow ranges from 3.2 to 13, with an average value of 9 m/s as described in [7].
2.3. Small vertical axis hybrid wind turbines

For the design of distributed generation systems, we will use the Darrieus and Savonius vertical axis turbine designs, which are optimal for turbulent winds that are generated in Peru. In turn, these independently have mostly different advantages and characteristics, but when used in a configuration that uses both designs, an adequate result is obtained for the areas studied [1].

![Figure 4. Hybrid vertical axis wind turbine model.](image)

The design of the Savonius type wind turbine which has a simple mechanism to build and therefore allows it to be more robust, in addition to starting it only needs low-speed winds however high-speed winds affect its stability (see Figure 4). On the other hand, the Darrieus type, has a great performance as shown in Figure 5, although to basically transmit angular velocity you must use a reduction mechanism to increase your torque to the shaft. In that sense, these features and parameters will be calculated within the CFD process.

![Figure 5. Performance according to design.](image)
3. Methodology

3.1. Design of a small hybrid VAWT

For the design of the vertical axis wind turbine (VAWT) to be analyzed in this research work, the Savonius and Darrieus rotor models will be used as a basis, which have been widely studied. Thus, when considering that we will have an increase in the final weight, we will apply composite materials such as carbon fiber and fiberglass to replace particular parts, and the blades that are manufactured in materials with great ease of manufacture such as aluminum, among other places of the same.

Then all the pieces will be assembled taking into account that the solid shaft that supports the rotor will have complete freedom to turn on its own axis as show in Figure 6.

![Figure 6. Design of the hybrid vertical axis wind turbine.](image)

Another point that must be taken into account is that this must be a shaft with high mechanical resistance, be drawn to ensure its straightness and have a standard diameter for its subsequent manufacturing and ease of work.

3.2. Conditions of the analysis

The analysis of the wind turbine will require the application of software that facilitates more specific calculations and of great difficulty such as the torque on the axis that generates the wind flow when it affects the rotor. In addition to determining and being able to visualize the vorticity that is generated around the rotor before different wind flows.

Other Based on the fact that this rotor design is omnidirectional, it is only necessary to do the analysis from the same direction. Otherwise, we will take a rotational value for the rotor between 10 rad/s and 40 rad/s because when this speed of rotation is exceeded, its efficiency drops by exceeding the maximum permissible values in standard electric generators.

In that sense, we will establish a control volume which will contain the rotor, a turning region which is the same rotor, the boundary conditions between which is the speed of entry of the air to the
control volume as shown in Figure 7 and also specify which are the values that we want to obtain in this case torque to the rotor shaft is one of these objectives.

4. Results and Discussion

Finally, the performance of the turbine that was designed will be analyzed, during the iteration period that the Solidworks software performed, we saw how the output parameters converged in iteration number 140 and also allows us to have them with their respective graph among other options such as visualizing the flow through specific sections as shown in Figure 8. The application of CFD is key to this performance analysis since it provides reliable values once it is built minimizing the associated error as we calculated in results [8].
4.1. CFD Simulation

To begin with the performance analysis, we will obtain the wind flow by means of transverse cuts to the axis with a distribution of 10, 40, 60 and 90 percent of its height for the same moment as the wind velocity and pressure are distributed within the control volume as is shown in Figure 9 and Figure 10.

Figure 9. Cross-sections of wind velocity on hybrid VAWT.

Figure 10. Cross-sections of wind pressure on hybrid VAWT.
The software, using the finite volume method, supports us in calculating the torque and force on the central axis as shown in Figure 11 and Figure 12 considering the wind force at constant speed; The evidenced result can vary over time, therefore, for a correct sizing, we are shown the maximum, minimum and average torques.

In addition to this, when we have assemblies like the one shown here, in which the axis is in movement, it is also possible to calculate the effect of the torque on the other components such as fins and support, since in some research studies have reached very efficient profiles in terms of useful energy.

![Figure 11. Torque (N.m) on hybrid VAWT calculated through CFD.](image1)

![Figure 12. Force (N) on hybrid VAWT calculated through CFD.](image2)

On the other hand, when suffering high torques or pressures end up suffering inelastic deformations or other kind of fails that in practical use are very harmful.

On the other hand, nowadays Computer Aided Engineering (CAE) has become paramount in research and investigation. For this reason, it was found through this work the need to apply computational fluid dynamics (CFD) since this allows a wide range of possibilities in design engineering and allows to identify faults in the turbine before it is built, avoiding economic and time losses during the manufacturing phase.
4.2. Performance study

The Betz limit is based on physical principles with which it applies to any wind machine. This 59% efficiency limit limits the possibility of subtracting the kinetic energy from the wind resource in a space.

A brief explanation is that to use or remove kinetic energy from the air it is necessary to allow part of it to dissipate sideways in the opposite direction to the flow of the wind since otherwise this would generate the accumulation of air mass causing the rotor stops in a few seconds.

In order to calculate the maximum power that a wind turbine like the one presented in this work could reach, we start from the coefficient of 0.15 according to what was explained in [5]. Below is equation (1) that describes the maximum power for this type of turbines.

\[ P_{\text{max}} = 0.15 \times H \times D \times V^3 \]  

Where:
- \( H \): Rotor height [m]
- \( D \): Rotor diameter [m]
- \( V \): Wind speed [m/s]

![Figure 13. Pmax graph obtained after 382 iterations by using CFD.](image)

The CFD application allows us to calculate the average value of the speed that affects the turbine in a more precise way, reducing the associated error. Therefore, the value of the maximum power shown in Figure 13 is more accurate and correct from the obtaining of the average speed on the surface of the wind turbine.

In the same way we see that by conditioning the input wind speed with 15 m/s we obtain an average speed in the turbine of 14.602 m/s and also with a maximum Power of 252,689 W.

This means avoiding an error of 2.73% in max power value that describe a better analysis by using computational fluid dynamics (CFD) [8].

This value is an approach and improvement for the dimensioning of wind machines oriented to projects of farms or wind farms, among other types of distributed generation projects that are so required in rural areas.
5. Conclusions

This brief analysis of the system includes several aspects such as the economic one, an intelligent application of vertical axis wind turbine designs and the orographic analysis of the rural areas of focus.

It is possible to democratize access to electricity through the application of low-cost wind turbines for distributed generation and autonomous systems in rural areas. Peru has sufficient wind energy potential in rural areas to be energy self-sustainable with respect to urban areas where geography does not allow it. Investment in wind generation systems should increase its presence in remote areas if progress is being made as a developing country.

Due to the feasibility that the implementation of this type of turbines must have, it is necessary not only to consider providing outreach to communities with lack of access to the electricity grid, but also to have a minimum wind resource to make it viable. For this reason, the province of Cajamarca was chosen due to what was previously explained, with which economic technical analyses can be carried out based on the research in this work.

The wind-induced energy capture capacity of a hybrid wind turbine is adequate under the conditions presented by the orographic analysis of the Peruvian territory, reaching an average of 6 watts using low-cost hybrid turbines.

The results obtained allow us to know the speed of the fluid around the assembly, how it affects each section and finally, how it restricts the fluid after passing through the design.

Although there are many results that allow us to see the flow of the fluid, in this application, we are using the "Cut plots" that allow us to review the effect of the fluid in each section of our VAWT hybrid. The application of these results in cutting, allows us to review the more or less efficient areas that can be improved in other applications, depending on input data such as fluid velocity.

Having performed the calculations using the CFD, greater reliability has been demonstrated in this type of analysis since we calculate the average speed in the turbine instead of taking only the wind speed. This makes calculations more effective, finally we have that the maximum power in a stable regime is 252 W. That is to say, during the winter weeks we will have enough power to power the low consumption luminaires and units with a single operating turbine.

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