The Air-Water Turbine

A new method of compressed air energy storage for power generation.

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Abstract:

In the context of growing concerns about carbon emissions and the pursuit of carbon-neutral targets, there is an increasing demand for clean electricity sources, such as wind and solar power. However, these clean energy options exhibit characteristics of instability and significant power fluctuations, which poses a challenge for the grid that requires stable power supply. As a result, a certain amount of power abandonment occurs due to the mismatch between energy supply and demand. To address this issue, the grid needs to incorporate peak-shaving power systems, often relying on thermal power generation, pumped water storage, battery storage, and compressed air energy storage.

When utilizing compressed air energy storage as a peak-shaving power system, it becomes necessary to pass the compressed air through a steam turbine to generate electricity during peak demand periods. This process, in turn, requires additional fuel, which introduces certain drawbacks, such as response time and cost inefficiencies. Consequently, clean power may still be partially abandoned. As electricity is a unique commodity without the brand attributes of typical consumer goods, users are primarily concerned with the cost per kilowatt-hour.

This article explores an innovative approach to utilize compressed air for peak-shaving power with a focus on achieving lower costs and improving transient response. The use of compressed air in pipeline power generation and air-water turbines plays a significant role in realizing these objectives.

Keywords: Steam turbine, compressed air, pipeline power generation, air-water turbine.

Introduction:

The current approach to peak-shaving involves using compressed air energy storage and reducing electricity production through steam turbines when the grid demands more power. However, this method suffers from drawbacks, including high peak-shaving electricity costs and slow response times. The primary cost driver is the steam turbine itself, which necessitates high-temperature, high-pressure gas to drive its power generation process. Consequently, additional fuel is consumed to generate the required high-temperature gas, further escalating electricity costs.

One of the reasons for the high cost and reduced efficiency lies in the design of existing steam turbines. These turbines employ a common rotor system for each stage, whether it is a wheel rotor or a drum rotor, with each stage operating at a different speed. As a result, the efficiency of each stage is impacted by the efficiency of the subsequent stage, leading to decreased overall efficiency.

Additionally, the blades used in current steam turbines feature a large, curved surface and twist angle (Figure 1). While this design is meant to enhance performance, it inadvertently results in a higher drag coefficient, resembling drag-type rotation turbines. This characteristic significantly lowers the efficiency of each level rotor. Although existing steam turbines may have over ten levels of rotors, their total efficiency remains suboptimal, contributing to their high cost.

Fig 1，Rotor blades in a steam turbine

Considering these challenges, there is a need for a more efficient and cost-effective solution to peak-shaving power generation using compressed air. This article aims to address these concerns by proposing an innovative design that incorporates lift-type rotation turbines, enabling higher tip rotation speeds and ultimately leading to improved efficiency and reduced costs.

Expression of wind power

In the wind power industry, the expression of the wind power (P) is: $P=(1/2)*1.225*\rho*S*V^3$ formula (1), where 1.225 is the air mass per unit volume，ρ、S、V are the efficiency of the wind turbine, the effective sweeping area of the wind turbine, and the speed of air flow. According to the above (formula 1), if the specific gravity per unit volume of air, the efficiency, the sweeping area of the wind turbine and the air flow speed is increased, then the power can be increased. Because the power and air flow velocity are cubic relationships, increasing the air speed has the most significant impact. This formula is commonly used to calculate the power of lift-type wind turbines, and it also applies to steam turbines. Therefore, this article focuses on how to improve the efficiency of steam turbine rotors at all levels by using specific cases based on aerodynamic characteristics. First, we set a basic condition. The power comes from compressed air input into a pipeline. In the pipeline, there are N levels of independently rotating wind turbines. These turbines have been designed according to the above formula (1). Each wind turbine is equivalent to an independent steam turbine rotor. Assuming that the internal circular cross-sectional area of this pipeline is 0.5 square meters, an auto-valve is installed at the entrance of the pipeline, which can automatically control the compressed air flow according to needs. In formula (1), increasing the air proportion can also increase the power, so atomizing water at room temperature can improve the proportion of air and efficiency of the pipeline power generation device.

To rectify turbulent airflow and improve the efficiency of the lift-type wind turbine, deflectors are positioned in front of each turbine. The deflectors can rectify the turbulence into a smooth air flow and the efficiency of the lift force type wind turbine can be greatly improved. Assuming that the flow rate of compressed air is 50 cubic meters per second, when the compressed air flows into the pipeline, the atomized water nozzle opens automatically to form a spray. The flow rate of atomized water is 13.5 kg/s. Because the compressed air flow rate is 50 cubic meters per second and the pipeline has an area of 0.5 square meters, the smooth airflow velocity with atomized water after rectification can reach 100m/s

In formula (1), increasing or decreasing the area of the air flow through the wind turbine can increase or decrease the power of the wind turbine. Because the flow rate is stable, increasing the area will increase the power. If the flow rate remains the same, increasing the area means reducing the speed of air flow. The flow rate reduces the power quickly; so, reducing the area will also reduce the power. But it will increase the air flow velocity, increase the air velocity, and increase the rate of power, which is far greater than simply increasing the area.

Therefore, a diversion cover can be added in front of the first-stage wind turbine. If the diameter of the diversion cover design is 50% of the pipe diameter, the flow rate will increase by 25%, from 100m/s to 125m/s. More importantly, the deflector can compress the airflow to the front half of the blade, which has the highest efficiency.

In the blade element momentum theory (BEM), when the tip speed ratio (the ratio of the blade linear velocity to the air flow velocity) reaches 4 to 6, the efficiency of the wind turbine is higher, and the theoretical limit value can reach nearly 59.3%. The efficiency of a blade is a function of the length of the blade. The blade tip section has the highest efficiency; the blade efficiency is lowest towards the root of blade, while efficiency at the centre of rotation of the wind turbine is nearly zero.

If the wind turbine has one blade, the efficiency of one blade is the efficiency of the wind turbine. With two blades, the efficiency of each blade will be reduced due to the turbulence of the former blade on the latter blade. The efficiency of the turbine is the sum of the efficiencies of the two blades, and the efficiency of the wind turbine with two blades is higher than with one blade. Using three blades is higher efficiency than two blades. The rotor speed will gradually decrease as the blade quantity increases. This characteristic satisfies the normal distribution. Power is the product of torque and rotation speed, and the product of the two (torque and rotation speed) should be maximized. In this article, the wind turbine uses 5 lift-type airfoil blades.

When the blade tip speed reaches the optimal linear velocity, the closer to the blade root, the lower the speed ratio and the lower the efficiency of the blade. Therefore, if the airflow speed is limited to the front half of the blade, the efficiency of the wind turbine can be greatly improved. If the blades and rotors are designed correctly, the average efficiency of each turbine can reach around 45% or even higher.

If the water atomization spray enters the pipeline with a water volume of 13.5 kg per second, and the mass of each cubic meter of the atomized water and compressed air is increased to 1.5 kg/m^3, the power of the first-level wind turbine P=(1/ 2) *1.5 (air density) * 0.45 (turbine efficiency) * 0.375 (sweeping area) * 125^3 (wind speed) = 247,192 watts, The RPM of the turbine will reach 15110.

In the above design, assuming the velocity of the air flowing through the first level turbine is 125m/s as V1, and the wind speed after flowing through the first level turbine is reduced to V2, the thrust T acting on the first stage wind turbine is: T=m (V1-V2), m=ρ*S*V, m is the flow quality per unit time. According to the pressure difference between the front and rear of the wind turbine, the thrust acting on the first level wind turbine can be expressed as T=S(Pa-Pb), where Pa is the air pressure in front of the wind turbine, and Pb is the air pressure that after the air through the turbine. The wind pressure behind the turbine can be obtained according to Bernoulli equation:

$1/2\rho V1^2+P1= 1/2\rho V^2+Pa$

$(1/2)\rho V2^2+P2=(1/2)\rho V^2+Pb$

$V=1/2(V1+V2)$

Let $V=V1(1-a)$, $V2=V1(1-2a)$

$V2/V1=(1-2a)$ is the ratio of the wind speed after the wind turbine to the incoming wind speed.

$a=(1-V2/V1)/2$，here, a is the turbulence factor before and after the wind wheel due to changes in wind speed.

$P=(1/2)*m*(V1^2-V2^2)$

$P=2\rho SV1^3*a*(1-a)^2$

Because the maximum power of the wind turbine occurs when dp/da=0, that is,

That is $dp/da=2\rho SV1^3(1-4a+3a2)=0$,

When a=1/3, that is (V2/ V1=1/3)

$Pmax=(16/27)*(0.5\rho SV1^3)$

$\rho=P/0.5\rho SV1^3$

$\rho max=16/27=0.593$

$a=(1-V2/V1)/2$

when V2 / V1 is 1/3,ρ=0.593

when V2 / V1 is 1/2,ρ=0.563

when V2 / V1 is 2/3,ρ=0.463

when V2 / V1 is 7/10,ρ=0.434

From the above calculation, it can be shown that the wind turbine efficiency ρ is 0.45, and the wind speed ratio of V2/V1 is approximately 0.68. Then the V2=0.68*125=85m/s. Knowing the air flow velocity of the wind turbine at next level, the parameters of that turbine can be designed. As V2 is 85m/s, if the diameter of the diversion cover in front of the secondary wind turbine is increased to 65% of the pipe diameter, and the area of the deflector has been increased by 15%, the resulting cross-sectional area of the airflow has then changed from the first wind turbine.

The 0.375 square meters of the turbine is reduced to 0.2925 square meters, and the corresponding air velocity is increased from 85m/s to 109m/s. The resulting power of the secondary wind turbine will reach 127,843 watts ($0.5*1.5*0.45*0.2925*109^3$).

If the diversion cover of the secondary wind turbine retains 50% of the pipe diameter, the power of the secondary wind turbine is only 0.5*1.5*0.45*0.375*853 = 77,725 watts. Therefore, the diameter of the diversion cover is increased by 15%, and the power is increased by 65%.

If the third-level turbine diversion cover still uses 65% of the pipe diameter, the airflow speed through the third stage is 109*0.68=74.12m/s, and the power of the third level turbine will be 40,198 watts ($0.5*1.5*0.45*0.29255*74^3$).

Should the diameter of the diversion cover continue to increase its size from 65% of the pipe diameter to 80%, the effective area flowing through the wind turbine will be compressed to 0.2482 square meters, and the wind speed flowing through the third level wind turbine will increase from 74m/. When it is increased to 87m/s, the power of the third-stage wind turbine will increase to 55,825 watts; an increase of 39% (0.5*1.5*0.45*0.2482*87^3).

The fourth, fifth, sixth, and seventh level wind turbines and the diversion covers would adopt the same parameters as the third level wind turbine, where the diameter of the diversion cover is 80% of the pipe diameter. The incoming wind speed of the fourth level wind turbine is 59.4 m/s, its power is 17,553 watts. The incoming wind speed of the fifth level wind turbine is 40.4m/s, and its power is 5,519 watts. The incoming wind speed of the sixth level wind turbine is 27.5m/s and the power is 1,735 watts. And the incoming wind speed of the seventh level wind turbine is 18.7m/s and the power is 545 watts.

The total power of the seven level turbines is 455,863 watts. The overall pipeline power generation device will reach 430kw if the average efficiency of each generator is 0.94.

If the size of each diversion cover is further increased to 80% of the pipe diameter, the wind speeds flowing through the seven levels of wind turbines are 276.3m/s, 187.9m/s, 127.8m/s, 86.9m/s, and 59m/s, 40.2m/s and 27.3m/s consecutively, the electric power of the first wind turbine will reach nearly 1.23 MW, the second turbine 385 kW, the third turbine 121 kW, the fourth 38 kW, the fifth 12 kW, the sixth 3.8 kW, and the seventh level is about 1.2 kW. The power of the seventh level will reach about 1.78 MW (fig 2).

In conclusion, the proposed design utilizes compressed air and innovative aerodynamic techniques to enhance power generation in steam turbines. The optimized system achieves higher efficiency and transient response, resulting in lower peak-shaving costs and reduced overall expenses for peak-shaving power generation.

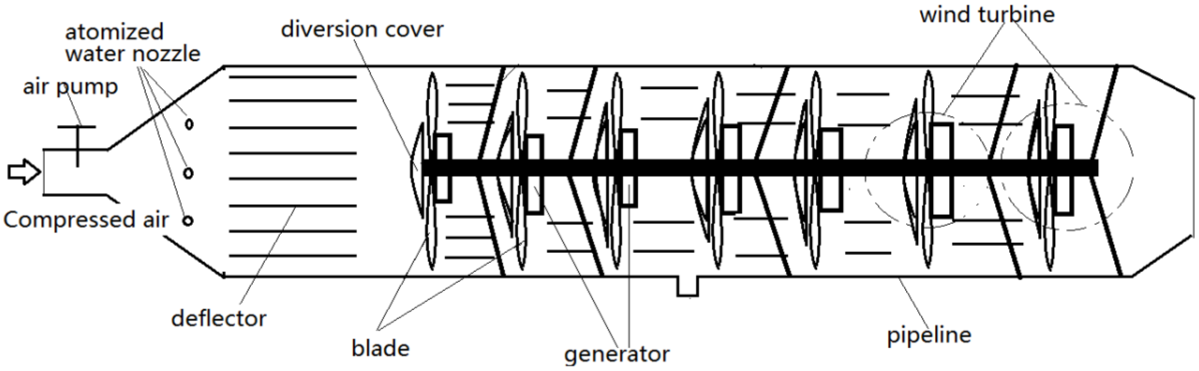

Fig 2, Pipeline Power Generation device

Results

This article presents the design methodology and outcomes of the Pipeline Power Generation device. The approach involves utilizing independent wind turbines at each level, eliminating the need for high-temperature gas, and incorporating various sizes of diversion covers to increase airflow speed in front of each level's wind turbines, thereby enhancing power generation efficiency.

In the context of carbon emission reduction and carbon neutrality goals, the primary concern for electricity users is the cost of electricity. Power generation and grid companies must continually embrace new technologies to offset the expenses of clean energy, thereby fostering the driving force for the sustainable development of clean energy.

Introduction to the Author:

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