New method of compressed air energy storage power generation- “air-water turbine”

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Abstract:

With the clarification of carbon emission and carbon neutral targets, human increasingly needs clean electricity, such as wind and solar power. However, clean electricity has the characteristics of unstable and large power fluctuations. But the grid requires relatively stable power supply. This creates a contradiction between energy supply and demand which results in a certain amount of power abandonment. Therefore, grid requires to be configured with peak shaving power according to a certain proportion, usually use thermal power generation, pumped water storage, battery storage, and compressed air energy storage. The steam turbine generates electricity when the grid requires more electricity. If compressed air energy storage is used as a peak-shaving power system, the compressed air must be passed through a steam turbine to power generation for peak-shaving. The steam turbine requires additional fuel. Even with a certain capacity of peak-shaving power, it still has some problems such as the response time and the cost of peak-shaving, the clean power will still be partly abandoned. Electricity is a special commodity and does not have the brand attributes of general commodities. What users need is the cost per kilowatt-hour. This article discusses how to use compressed air to obtain lower peak-shaving power costs and achieve transient response.

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

Introduction:

The existing peak-shaving method uses compressed air energy storage and reduction the electricity through the steam turbine when the grid requires electricity. Not only the cost of peak-shaving electricity is high, but the response time is slow. The main cost is the cost of steam turbine. The steam turbine requires high temperature, high pressure gas to drive the turbine to power generation. The steam turbine requires additional fuel changing to high temperature gas to drive the turbine to power generation. The result is high cost of peak shaving electricity and further increases the cost of electricity. The reason is that the existing steam turbine requires high temperature and high pressure gas to drive the rotors of the turbines at each stage, whether it is a wheel rotor or a drum rotor, and each stage of the turbine is a common rotor system, and the speed of the previous stage turbine is higher than that of the next stage rotator of turbine. The high speed rotor drives the low speed rotor, and finally the rotors together drive the steam turbine rotor to generate electricity. In this way, the previous-stage turbine will drive the next-stage turbine to rotate, and the efficiency of the previous-stage turbine is lowered by the efficiency of the next-stage turbine. At the same time, the blades of the existing steam turbine use the airfoil with large curved surface and large twist angle (Figure 1). A rotor with a large curved surface and a large twist angle causes a bigger drag coefficient and too many blades are not conducive the rotor to obtain a higher tip rotation speed (the ratio of the tip linear velocity to the speed of the blade). Therefore, the rotor of the existing steam turbine is closer to the drag type rotation turbine, and the efficiency of the drag type wind rotation turbine is lower much than the lift type rotation turbine. The efficiency of each level rotor is lower. Constrained by this condition, although the existing steam turbine has more than 10 levels rotors, but the total efficiency of steam turbine is not high, and the cost is much high.

Fig 1, blades of rotor in steam turbine

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), 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 increase the specific gravity per unit volume of air, the efficiency, the sweeping area of the wind turbine and the air flow speed, the power can be increased, but because the power and the air flow velocity are cubic relationship, the effect of increasing the air speed is the more best. This formula is used to calculate the power of various lift-type wind turbines, and it is also applicable to steam turbines. Therefore, this article will use specific cases based on aerodynamic characteristics to focus on how to improve the efficiency of steam turbine rotors at all levels.

First, we set a basic condition. The power comes from compressed air. The compressed air is 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 rotor of steam turbine. Assuming that the internal circular cross-sectional area of this pipeline is 0.5 square meters, a auto-valve is installed at the entrance of the pipeline, which can automatically control the compressed air flow according to the needs. In formula (1), increasing the air proportion can also increase the power, so atomizing water with room temperature can improves the proportion of the air. It is used in the pipeline power generation device.

In classical steam turbines, the air flow is turbulent, which reduces much the efficiency of lift-type wind turbine. Therefore, a number of deflectors are arranged in front of each level of the wind turbine. The deflectors can rectify the turbulence into a smooth air flow.

The efficiency of the lift force type wind turbine can be improved greatly. 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, the pipeline with 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, but because the flow rate is stable, increasing the area will increase the power, but because the flow rate keeps the same, increasing the area means reducing the speed of air flow. The flow rate reduces the power quickly; 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 much greater than the rate of increasing the area. Therefore, a diversion cover can be added in front of the first-stage wind turbine. If the diameter of the design diversion cover is 50% of the pipe diameter, the flow rate will increase by 25%, from 100m/s to 125m/s. s. More importantly, the deflector can compress the airflow to the front half of the blade, and the front half of the blade 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, 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 toward the lowest at the root of blade. The efficiency at the center of rotation of the wind turbine is nearly zero.

If the wind turbine adopts one blade, the efficiency of one blade is the efficiency of the wind turbine; if the wind turbine adopts 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 the wind turbine with one blade; the efficiency of the wind turbine with three blades is also higher than the wind turbine with two blades. The higher the multi-efficiency, when the number of blades is increased, the rotor speed will gradually decrease with the increase of the blade quantity. 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 improved greatly. If the blades and rotors are designed properly, 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 turbine will reaches 15110.

In the above design, assuming that 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 wind 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)

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

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

ρmax=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 known that when the wind turbine efficiency ρ is 0.45, the wind speed ratio of V2/V1 is approximately 0.68. Then the V2=0.68*125=85m/s.

On the basis of knowing the air flow velocity of the wind turbine at next level, the parameters of the next level wind turbine can be designed. Because V2 is 85m/s. But if the diameter of the diversion cover in front of the secondary wind turbine is increased to 65% of the pipe diameter, the area of the deflector has been increased by 15%, and the cross-sectional area of the airflow is changed from that of 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. then, the power of the secondary wind turbine will reached 127,843 watts ($0.5*1.5*0.45*0.2925*109^3$).

But if the diversion cover of secondary wind turbine keeps 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%.

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

But if the diameter of diversion cover continue to increase the 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 s is increased to 87m/s, the power of the third-stage wind turbine will increase to 55,825 watts, increase by 39%. $(0.5*1.5*0.45*0.2482*87^3)$

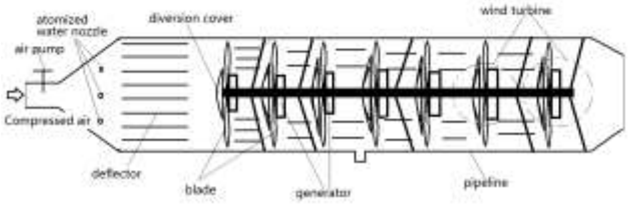
If the fourth, fifth, sixth, seventh level wind turbine and the diversion cover adopt the same parameters as the third level wind turbine, the diameter of the diversion cover is 80% of the pipe diameter. The incoming wind speed of the fourth level wind turbine is 59.4 m/s, its power is 17,553 watts; The incoming wind speed of the fifth level wind turbine is 40.4m/s, its power is 5,519 watts; the incoming wind speed of sixth level wind turbine is 27.5m/s and the power is 1,735 watts; the incoming wind speed of 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 device of pipeline power generation 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 wind turbine are 276.3m/s, 187.9m/s, 127.8m/s, 86.9m/s, and 59m/s, 40.2m/s and 27.3m/s, the electric power of the first wind turbine will reach nearly 1.23 MW, the second wind turbine is 385 kW, the third wind turbine is 121 kW, the fourth is 38 kW, and the fifth is 12 kW, the sixth is 3.8 kW, the seventh level is about 1.2 kW, and the power of the seventh level will reach about 1.78 MW (fig 2).

Not only it has the higher power, but also the characteristics of the transient response can be obtained which will let the peak-shaving cost is lower, greatly reducing the cost of peak shaving power.

Fig 2, the device of pipeline power generation



Results

This article presents the design method of the above-mentioned pipeline power generation device and the results obtained. Here, the wind turbines of each level are independent, and high-temperature gas is not required, and different sizes of diversion covers are used to increase the airflow speed in front of the wind turbines of each level for increasing the power generation.

Electricity is a special commodity, and users only concern about the cost of the electricity. Under the overall goal of carbon emission and carbon neutrality, the power generation companies and grid company need to continuously adopt new technologies to neutralize the cost of clean energy in order to obtain the driving force for sustainable development of clean energy.

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