Efficiency of wind turbine formula

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We may think that the bigger and more efficient these wind turbine generators are, the more energy they will produce. But there is a maximum limit to the efficiency of any wind turbine generator in converting the energy of the wind into usable energy and this is known as the Betz Limit.

The Betz Limit, or Betz Law, calculated by German physicist Albert Betz nearly a century ago, states that no wind turbine generator can convert more than about 60% of the kinetic energy of the wind into mechanical (or electrical) energy simply be turning the blades of a rotor.

Since wind moves erratically around from place to place carrying with it kinetic energy, wind direction and wind velocity are therefore subject to both rapid and frequent changes. So any wind turbine must be designed to respond to both conditions as it rotates about a central axis.

Generally, a wind turbine generator (WTG) generates power (P) proportional to the volumetric flow of the wind through it. This results in a pressure difference between the wind entering the rotor blades swept area and leaving it as energy is extracted as it does so.

The Coefficient of Power (CP) allows us to calculate the total amount of power a wind turbine is producing from the total energy available in the wind at a particular wind speed. For example:

So the conversion power of a wind turbine is related to design and is defined as the ratio of the net power output to the wind energy input. But the actual power available to rotate the turbine blades is only a fraction of the total theoretical power available in the wind as friction, drag and the swirling action of the air around the wind turbine rotor blades all contribute in reducing efficiency. Therefore, not all the wind’s energy is converted into usable mechanical (or electrical) energy due to these additional losses.

We know that wind turbines convert the winds energy into mechanical or electrical energy as a direct result of slowing down the oncoming wind as it transfers part of its linear kinetic energy to the rotor blades.

Clearly, if the turbines rotor was constructed as one solid disk design it could not pass any wind energy at all, so it would not be rotated by the wind and therefore no kinetic energy would be extracted or converted.

If we go to the other extreme where a wind turbine had just one single thin rotor blade. Possibly 90% or more of the oncoming wind energy would pass directly through the rotational (swept) area of the single turbine blade missing it completely. Therefore, very little of the winds linear kinetic energy would be converted using a turbine generator with just one single rotor blade.

So there has to be some middle ground in which the number of rotor blades, the volume of air passing through the swept area, as well as the limitations and vortex effect behind the rotor blades produces the ideal or theoretical maximum efficiency from a available wind.

Where: P is the power in watts, ρ (rho) is the air density in Kg/m3, A is the circular area (πr2 or πd2/4) in m2 swept by the rotor blades, V is the oncoming wind velocity in m/s, and CP is the power coefficient (efficiency) which is the percentage of power in the wind that is converted into usable energy.

Thus, the wind power output is directly proportional to the cubic power of the wind velocity and to the square of the diameter of the wind turbine. Which is interesting to note, because, when the wind velocity is doubled, the power output is increased by a factor of eight.

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