FRENCH WIND GENERATOR SYSTEMS

John M. Noel

Aerowatt Corporation
Paris, France

HISTORY OF THE LARGE FRENCH 800 KILOVOLT-AMPERE WIND GENERATOR

B.E.S.T. (Bureau d'Etudes Scientifiques et Techniques) was a consultant engineering firm in the field of applied aerodynamics. This company worked for 18 years on contract for the French Electricity Authority (E.D.F.) in the field of wind power. B.E.S.T. was dissolved in 1966, and the newborn Aerowatt Company acquired the know-how, the patents, and the staff of B.E.S.T. that were involved in wind power. The Chief Engineer of the 800 kilovolt-ampere wind generator project is now the Technical Director of Aerowatt.

The Project

The objective was to design a wind driven generator with a rated power of 800 kilovolt-amperes, capable of being connected to the main network. It was an experimental machine and not a prototype.

The rotor was a three-bladed propeller. Each blade was twisted. The fixed pitch of the blades was, however, adjustable. Other aerodynamical features are

Diameter of propeller, m (ft)	31 (105)
Starting wind speed, m/s (mph)	7 (15.6)
Rated wind speed, m/s (mph)	22 (49)
Survival wind speed, m/s (mph)	56 (130)
Nominal rotation speed, rpm	47

The asynchronous, 800-kilovolt-ampere generator was driven by the propeller through a gearbox. In the event of a no-load condition in the network, the machine was connected to a dissipating resistor made of iron wire located on poles (to prevent overheating).

The hub was supported by a vertical, pivotable tower having the length of a blade. The pivot rested on the top of a three-legged pedestal at a height of 33 meters. The entire system could be tilted about a horizontal axis going through the feet to two legs. So with the aid of winches, it was possible to lower the hub for maintenance and repair.

Tests

The machine was located near Nogent Le Roi, a small country village 120 kilometers west-southwest of Paris, in a wide flat plain. The site was reasonably gust-free.

The first propeller on the machine lasted 18 months without any trouble, and the generator was connected many times to the network. Sometimes the delivered power reached 1.2 megawatts. We do not know the total energy delivered by the machine during the period.

To improve the characteristic, the rigid propeller was replaced with a flexible one. Tests in a wind tunnel had shown a flutter effect on such blades. Nevertheless, the new propeller was installed. Experience demonstrated the wind tunnel tests to be correct: one blade was broken; the hub was then destroyed by the unbalanced torque. It was the end of the E.D.F. experiment on large-scale wind machines. It ran for 18 months from 1958 to 1960.

Results

The results of this experience were the following:

The breakdown of the second propeller due to a flutter effect led B.E.S.T. to make a thorough study of this point and to find ways to avoid such a phenomenon on new propellers. We have since designed long, slender propellers without having any trouble.

We believe we now have the knowledge necessary to build a large-scale wind driven generator.

TODAY'S USES OF WIND POWER

Wind energy is free but it has two drawbacks for a normal use: its short term, random character and its power varies as the cube of the wind speed.

In the recent past interest in the wind energy has declined because of the developments of networks and heat engines. At the same time the need for small, remote power sources has grown. The development of solid-state electronics has enabled stations of any type to be unattended as long as the life of the equipment. For instance, 20 years ago a microwave relay station needed kilowatts of power; nowadays only a few dozen watts are needed. Then, a major lighthouse was fitted with a 6-kilowatt lamp; now, with a 1-kilowatt halogenous lamp.

The Wind Motor

We can split a wind generator into two parts: the wind motor (i.e., the propeller, the hub, and the rudder-fin) and the generator.

The problem with the wind motor is that it must meet two opposite requirements: It must deliver full rated power at low wind speeds to overcome the need for energy storage; and it must be automatically transparent to the high wind speeds.

We have designed autoregulated machines which meet the second requirement. Six major lighthouses have been fed by such machines for 15 years. We have seldom stopped the machines with the centrifugal brake, but these machines do not meet the first requirement. They are only useful in high wind areas (Around Brittany the average wind speed is about 10 m/s, i.e., 25 mph.). So we think the solution to the problem can be found only in the variable pitch propeller.

The characteristics of all present Aerowatt wind generators are the following:

Average starting wind speed, knots	3 to 6
Average wind speed necessary for power delivery, knots	6
Nominal wind speed at full power, knots	14
Rotation governor efficiency (wind speed, over 14 knots; load-no-load speed ratio)	5
Survival wind speed, knots (m/s)	120 (60)

The Generator

All the Aerowatt generators are permanent magnet ones. Hence, no excitation power is required. The generator output is ac current, which is easier to handle than dc. In addition no maintenance is required. For medium range machines the delivered current is of the industrial type: three phases ac, 50 c/s.

Survival in Extreme Conditions

In sandy areas the problem is the blocking of ball bearings or slip rings with sand. This problem is overcome with sealed ball bearings and tight bodies. Propellers are protected against erosion with a Neoprene coating.

In icy areas the most dangerous enemy for the wind generator is sleet. Two ways of beating this enemy are

(1) oversized machines, able to withstand, at nominal rotation speed, the unbalanced torque given by a 1-inch-thick layer of ice on only one blade, and

(2) Teflon coated hub, blades, and rotor to reduce the adhesion of ice.

Several years experience with these machines in the Alps and in Norway has shown that these methods of reducing the chances of damage caused by sleet are successful.

Storing the Energy

For small machines or small installations, the random wind power production is smoothed by storing electricity in a battery bank. Aerowatt has combined the off-load working ability of its machines with the ac delivered current in a solid-state control device, which stops the rectifier when the gassing voltage of the battery is reached. So, in temperate climates, there is no need to add water to the battery within a year.

For medium machines it is possible to install a diesel generator in parallel with the wind-driven one. Energy is stored in a negative way, that is, by saving diesel oil when the wind blows.

Ultimate Power Source

Primary Cells. - The industrial uses of energy require a no-break power supply, so Aerowatt delivers with the small machines a bank of primary cells that are able to deliver a steady current of 5 amperes, with a capacity of 1000 ampere-hours. These primary cells have a shelf life of 3 years.

Diesel Engine. - The wind-driven generator control boxes are fitted with special circuits enabling it to start a diesel engine when the main battery bank is discharged and to stop it when full charge is reached.

Conclusion

Aerowatt has developed a comprehensive system (see table I and figs. 1 to 3) based on wind power able to meet industrial requirements for power in remote areas for unattended stations.

NOTE ON THE UTILIZATION OF WIND POWER FOR PROVIDING INDUSTRY ELECTRIC POWER IN THE FUTURE

Wind power has always been used to meet the human needs, either to provide driving power to windmills, or once transformed into mechanical power to propel ships. Nowadays one is interested in transforming this potential power into electric power, the easiest form of power to use. Studies and tests have been carried out during the last decades to apply this transformation industrially, that is, to provide electric power to a distribution network.

Machines with a 1200-kilowatt nominal power rating have been built. And the Aerowatt Company has the technical data of the B.E.S.T. 800-kilovolt-ampere wind generator. However, none of the machines that we know of ever made use of standardized applications. We believe that these large machines failed because they were too complicated, and therefore, too expensive. The price of the supplied kilowatt-hour was too high as compared with that provided by other sources, for example, fossil fuel plants or water power. This was due to the basic characteristics of wind power, namely, it is impossible to store, and it is impossible to forecast when the wind will blow.

Let us compare wind power with water power. We notice that, at least originally, they are both random. It is difficult to forecast whether it will rain next week, and in the same way it is impossible to forecast whether the wind will blow. Water power can be stored in the form of potential power, on the one hand thanks to mountainous areas and to water mean flow speed, and on the other hand by the creation of dams (artificial storage). As far as wind is concerned storage is not so easy.

However, the "Comite Technique pour l'Etude du Vent" has made observations over a few years, and these observations have shown that the average annual wind velocity on a given site does not vary much, about 20 percent.

Existing Possibilities

We have stated here that previous efforts to master wind power failed because of the high price of power supplied to the network. Actually, if we look closer at the machine we know best, the BEST-ROMANI 800 kilovolt-ampere machine, we note that it was equipped with a three-blade 30-meter-diameter propeller and that it supplied 800 kilovolt-amperes for a wind velocity of 22 meters per second. Moreover, the aerodynamical regulation did not allow the machine to operate off the network, and a brake had to be provided so that the machine would not race if the connections with the network were interrupted. The twisted-wing propeller was difficult to build. Finally, the machine, a purely experimental one, was too expensive for the relatively low power supply.

We believe that the problem has been solved since the Aerowatt Company designed and built a variable pitch propeller which operates far better than the other existing variable pitch propellers. Thanks to this propeller, wind-driven generators have been built that can provide their rated power as soon as the wind speed has reached 7-meters-per-second (14 kts). For example if we consider the chart of wind velocity characteristics on a site off the French coast, Sept Iles, we notice that this wind velocity (7 m/s) is reached or exceeded 72 percent of the time, whereas the 22-meter-per-second wind velocity is reached or exceeded only 1.5 percent of the time. As soon as the nominal wind velocity is reached or exceeded, the machine rotational speed is constant to $\pm$ 1 percent, whatever the wind variations are, of course, within the machine-power limits. The variable pitch allows the machine to keep its normal characteristics even for high wind speeds (up to 60 m/s). In short the Aerowatt variable pitch propeller allows us to build machines that, over a year, operate at their nominal power for a greater number of hours than the machine built heretofore. The result is due to the simplicity of the design. Under given conditions electric power could be supplied at a price that is more competitive with steam-plant produced power.

Machine Structure

The Aerowatt high power wind-driven genérator has the same structure as the low and average power wind-driven generators built up to now with, however, some operation improvements in consideration of the machine size.

The Propeller. - As for the other Aerowatt wind-driven generators it is a two-wing propeller regulated by pitch variation and maintained at the stalling limit. The propeller wings are made of extruded aluminum alloy, and have a constant section. They are guyed with compensated stretch guys.

If necessary, they can easily be coated to protect them from ice deposit or sand erosion. The wing setting is calculated so that the propeller reaches its maximum efficiency within the more common wind velocity range, usually 3.5 to 7 meters per second.

The design propeller nominal rotation speed is limited to a 90 meter per second relative wind speed (vector sum of the wind speed and rotation wind speed) at wing tip. Thus the aerodynamical flows always remain within the low subsonic range.

The hub has two kinds of springs: the starter springs and the regulation springs. The starter springs set the rotor blades, when at rest, to a value high enough, in relation to the wind, to get a starting torque larger than that for $V > 3$ meters per second. The regulation springs compensate for the centrifugal force on the blades by controlling the setting so that the rotation speed remains constant, independent of the wind, once it has reached its rated value.

The Mount. - The mount holds a spindle, the step-up gearbox, and the pivot. The shaft of the spindle is connected on one end to the propeller hub and on the other to the step-up gear train by means of a coupling. The step-up gearbox brings the propeller rotation speed to such a value that the coupled electric generator supplies an industrial-frequency electric current. The pivot allows the machine to swivel windwards under the action of the vane moment. The pivot also holds the sliprings, which transfer the electric power supplied by the generator towards the distribution network.

The lower part of the pivot is fitted on the driven generator support. The upper part is connected to the mount by a spindle assembly. The pivot is protected by a flange of the same length. The flange is connected to the mount and carries a ladder which provides access to the mount.

Of course the center of gravity of the machine moving parts is adjusted so as to lie on the pivot axis.

The Vane. - As for all Aerowatt wind-driven generators, the propeller rotation plane is located up wind of the pivot. So located, the propeller operates in a stream which is not disturbed by the pivot wake. The main purpose of the vane is to keep the propeller rotation plane perpendicular to the wind. The vane essentially consists of a surface fitted at the end of a long shaped support linked to the mount rear part. This surface, the tail fin, tends to stay in the wind stream. If it deviates from this position or if the wind direction changes, the thrust on the tail fin no longer goes through the pivot, and a return moment places the propeller rotation plane perpendicular to the wind direction.

The high power wind-driven generators are equipped with a new device designed by Aerowatt. This device limits the yaw rotational speed to a preset value and, in consequence, limits the stresses due to gyroscopic effects on the propeller. This is very important for the propeller mechanical strength.

Limits for use. - We shall consider the following type of operation: supply power to a small distribution network, not connected to a national network, using a heat engine plant with "n" generators of "p" kilovolt-ampere unit power driven by diesel engines as the power source. If the network under consideration is in a very windy area, or is so far from the usual sources of petrol products that the latter once delivered are very expensive, then the price of power supplied by the high-power wind-driven generators would then be lower than that of the fuel necessary for diesel engines to supply the same power.

Operation conditions. - The wind-driven generator has a quasi-constant power. Yet, taking into account the characteristics of the Aerowatt wind-driven generators, the power that is supplied to the network when the wind speed ranges between the starting speed and the nominal speed is negligible.

On the other hand, the wind-driven generator has a low operating cost, in that the primary source of power is free, and the maintenance expenditures are very little. So, once money has been invested in a wind-driven generator, it is desirable to use all electric power it supplies.

Under the limits of use already specified, the costs of the diesel-driven generator includes the price of the fuel used and the price of the maintenance, as diesel engines require periodic maintenance which is a function of the operating hours. It is thus desirable to use the diesel engines as little as possible.

The normal operation of the electric network, however, adds new restrictions. The power required by this network must be supplied at any time, independent of the wind conditions. The frequency of the supplied electric current must remain within narrow limits. And the required power varies over a short period of time according to human needs. Clearly, it is impracticable to have alternately periods when power is supplied exclusively by diesel-driven generators and periods when power is supplied exclusively by wind-driven generators, because there are transition periods when the wind speed comes to the starting threshold and then to the rated productivity threshold, either increasing or decreasing, and periods when the network requirements increase. It is our belief that the best solution consists in having a diesel-driven generator in continuous operation. This generator would have two main functions: It would define the frequency of the electric current supplied to the network, and it would absorb the rapid variations either of the power required by the network or of the power supplied by the wind-driven generators when the wind speed ranges between the starting threshold and the rated power threshold. Under these conditions the wind-driven generators will be coupled to the network most of the time. We are sure that this will be easier if the electric generators coupled with the wind-driven generators are asynchronous, as they are strong electric machines that are perfectly suited to wind-driven generators.

The idle power necessary for network operation can be supplied either by the power generator or generators still working and at least partly by the batteries of the condensers.

Adapting the Wind Driven Generator to the Site

Figure 4, curve A, shows the theoretical maximum specific power that can be taken from the wind according to BETZ theory; that is,

$$W = \frac{16}{27} \times \frac{1}{2} \rho V^3$$

Yet to take off the whole wind power would mean that the wind speed downwind of the propeller would be zero, which of course, is impossible. Curves B_1, B_2, and B_3 of figure 4 show the variation of the specific power output actually supplied by the propeller with wind speed for three different values of rated wind speed, 7, 9, and 11 meters per second.

Figure 5 shows the probabilities θ for having a given specific power (kW/m^2) (Power duration curve) taking the three characteristics of figure 1 as parameters and taking into account the data of the V(t) function in two places:

(1) Sept Iles lighthouse, northern coast of Brittany, France, where $\phi = 48^o\ 53'$ N, $G = 3^o\ 10'$ E, and the mean wind speed is about 8.5 meters per second

(2) Johannesburg, South Africa, where $\phi = 26^o\ 18'$ S, $G = 27^o\ 10'$ E, and where the mean wind speed is about 4.8 meters per second.

Aerowatt systematically chose to adapt its low- and average-power wind-driven generators according to curve B_1; that is, the machines start between 3 and 3.5 meters per second and supply their maximum power around 7 meters per second. This allows a greater use range of wind-driven generators to areas where it was not possible to use them hitherto; and at the same time in the other areas it facilitates the storage of electric power as the number of productive hours is increased.

However, in the areas defined in the section <u>Limits for use</u> where high-power wind-driven generators are to be used and according to the regularity wanted, it can be economical to modify the wind-driven generator decreases with the propeller diameter. If at a given site the percentage of time during which the wind speed exceeds 9 meters per second for example is close to that during which the wind speed usually exceeds 7 meters per second, it is desirable to choose a nominal speed of 9 meters per second for the propeller diameter will be reduced by $(9/7)^{2/3} = 1.46$. Moreover the reduction of the mechanical multiplier gearbox, and of course its price, is linked to the dimension of the propeller, for a smaller propeller can rotate more rapidly and the multiplier will thus have a lower torque to transfer and a smaller velocity ratio to provide.

Figure 5 gives an example of the diameter evolution of a wind-driven generator supplying an average power of 50 kilowatts at nominal speed if it were installed in Sept Iles.

Power of Wind-Driven Generators to be Built

Table II gives the approximate dimension of wind-driven generator propellers according to their power, for a 7-meter-per-second nominal speed.

Building a wind-driven generator with a propeller diameter of 45 meters does not require expensive technologic methods. With a propeller of the same size and a nominal speed of 11 instead of 7 meters per second, the wind-driven generator could supply a power of about 400 kilowatts; and with a nominal speed of 22 meters per second, like the machine built in 1958, the power supplied would be 3000 kilowatts.

Table III gives a different view of this question. It shows how the choice of different adaptation speeds affects the main parameters of a wind-driven generator, this in the site of Sept Iles, the power supplied over a year being maintained constant.

DISCUSSION

Q: What is the cost of these units? Do you have any estimates of either the smaller ones or the larger ones of those units?

A: Yes. I can give you some ballpark price for f.o.b. machine in the U.S.A. The costs start from $1800 for the little one, the 24-watt machine, up to $10 000 for the 4 kilowatt machine including the machine itself, the rectifier, the controls, and so forth.

Q: Will you describe the 800-kilowatt machine; its size, the number of blades, and other characteristics? I might add that I have had a great deal of difficulty finding literature on the efforts in France, so anything you could tell us would really be helpful.

A: This big machine was a three bladed one. It was running on the principle of autoregulation. That is to say it was fixed pitch, but the speed of rotation limitation was done by the difference of the slope of the generator itself and the curve of the propeller. The propeller was located downwind of the pivot.

The structure was able to swing around the wind rotor axis so that the machine could be built on the ground and not on the top to save some money.

The span was 31 meters, roughly 110 feet. The rotation speed was 47 rpm, the cut-in wind speed, as I already said, was 14 knots, and the rated wind speed was 45 knots. That is the reason why we think this machine was only experimental. Such windspeeds are only available about 5 percent of the time.

It ran very properly for 18 months. The problem was when we installed the flexible blades, we had trouble with flutter and no more blades.

Q: What year was this?

A: It ran from 1958 to 1961.

Q: Why did you switch from rigid to flexible?
A: To try to improve the wind speed and to reduce the rated wind speed.

Q: Do you remember what the cut-in speed was with the flexible blade?
A: It was the same cut-in speed, 14 knots.

TABLE I. - SOME FIGURES ON AEROWATT BIG WIND GENERATORS

Model No.	Span, ft	Rotational speed, rpm	Total blade weight, lb
4100FP7	31	150	130
15KFP7	59	75	1 000
50KFP7	107	45	6 000
100KFP7	153	30	16 000

TABLE II. - RELATION OF PROPELLER DIAMETER TO OUTPUT POWER

Rated power kVA	Propeller diameter, m
4.1	9.2
15	18
50	32
100	45

TABLE III. - EFFECT OF ADAPTATION SPEED ON MAIN PARAMETERS OF A WIND-DRIVEN GENERATOR

Adaptation speed, V, m/s	Generator rated power, P, kW	Propeller diameter, θ meters	Torque on propeller shaft, C, m·kg
7	60.6	32.5	1552
9	68.5	25.7	999.5
11	82	28.8	790

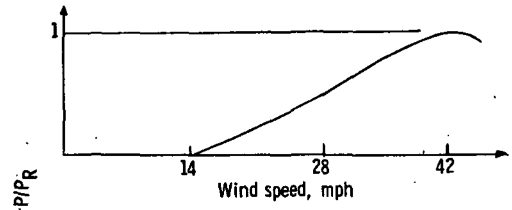

Figure 1. - 800 KVA B.E.S.T. machine.

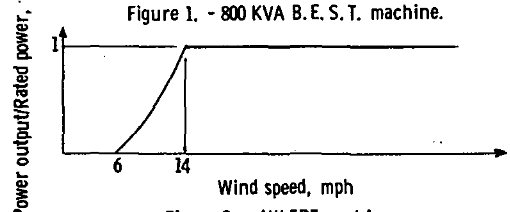

Figure 2. - AW FP7 machines.

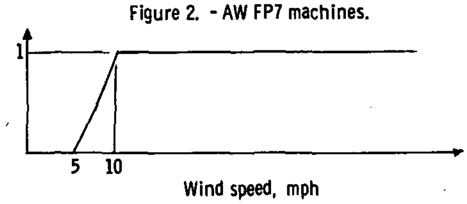

Figure 3. - AW FP5 machines.

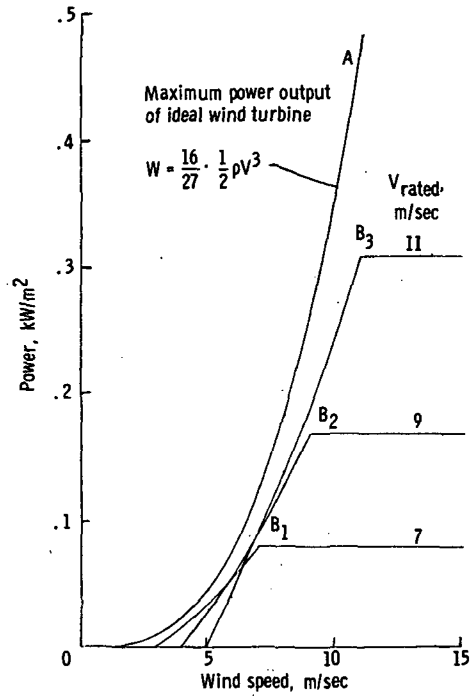

Figure 4. - Power output characteristics of wind generators having various rated wind speeds.

	Johannesburg			Sept Iles		
Rated wind speed, V_R, m/s	7	9	11	7	9	11
Average spec. power, $\bar{P}$, kW/m^2	0.036	0.052	0.060	0.66	0.124	0.19
Rated spec. power, P_m, kW/m^2	0.08	0.17	0.31	0.08	0.17	0.31
Ratio $P_m/\bar{P}$	2.22	3.27	5.5	1.21	1.37	1.64
Equivalent percent time, τ, at rated power operation	45.5	30.3	20	82.5	73	61
Rotor area diam., φ, m	1.0	0.84	0.77	1.0	0.73	0.59

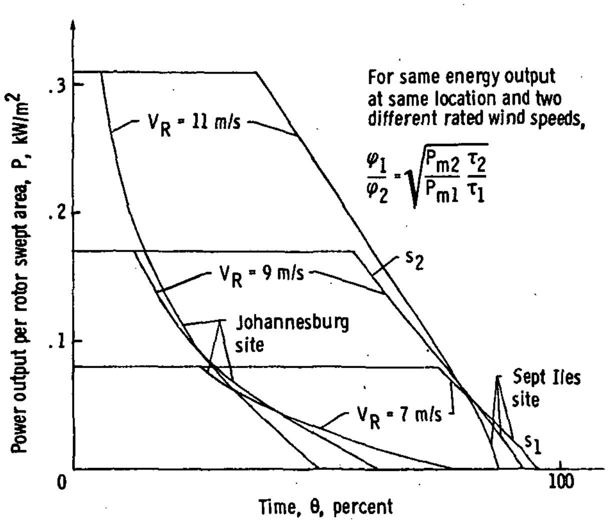

Figure 5. - Power output duration (cumulative frequency) curves for wind generators operating at Johannesburg, South Africa (mean wind speed, 4.8 m/s), and at Sept Iles lighthouse on North Coast of France (mean wind speed, 8.5 m/s) and for rated wind speeds V_R of 7, 9, and 11 m/s.

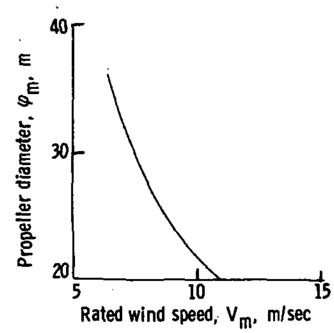

Figure 6. - Propeller diameter as a function of rated wind speed for a wind generator having 50 kilowatt rated output and sited at Sept-Iles Island.