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Performance Measurements on the
2 kW Dunlite windgenerator

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R-469-D

February 1981

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Laboratory of Fluid Dynamics and Heat Transfer
Dept. of Physics
Eindhoven University of Technology
Performance measurements on the 2 kW Dunlite windgenerator at an open test site are reported. The measured overall efficiency (electric output related to the power in the wind) of the machine was rather low (0.10). Probably this can be approved by a better aerodynamic lay-out of the rotor, a better matching of the rotor to the generator, more adequate operating of the safety system, and/or an altered design of the regulator.

The measurements are compared with the windtunnel measurements of Hinsley and Smith, in Australia, and with the open test site measurements in Bohus Malmö, Sweden.

ACKNOWLEDGEMENT

The authors like to acknowledge the contribution to this study of H. van Leeuwen, A. Huismans, L. Wasser, E. van Voorthuisen, B. Wijnands and A. Prijt of our laboratory; and of the students T. van de Boomen, F. Föllings, H. Kuiper and J. Mulder.
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1. **INTRODUCTION**

In 1977 Mr. Begeman of Energy Systems, Philips Eindhoven contacted our group, concerning the utilization of wind energy. Philips' Energy Systems were interested in the performance of the 2 kW windgenerator, produced by Davey Dunlite of Pye Industries, Australia [1].

In May 1978 a contract was signed between the University and Philips. The latter would make available the above mentioned windgenerator, the former would carry out measurements to determine the quasi-static power output performance of the generator. No further financial transactions were involved. The work was to be performed by students.

A few months after the contract had been signed, it turned out that the group Philips' Energy Systems had been discontinued.

There has been rather a great delay in obtaining the measurements. The generator was installed on the roof of the High Speed Laboratory Building in September 1978.


The underlying report summarizes the main results of [2] through [5].

In the past field measurements on the same type of machine in Bohus Malmö, Sweden were reported in [6]. Windtunnel tests on rotor and generator were carried out by Hinsley and Smith [7] in Australia.
2. DESCRIPTION OF MACHINE

The machine is a DC Brushless 2 kW wind-driven generator, type BC, for 110 V DC-operation, of Davey Dunlite Division of Pye Industries Sales PTY Ltd. A side-view drawing and a photo are shown in fig. 1. A detailed description (including serial numbers) is given in Annex I. The same machine is also available on the market as Quirk's brushless wind-driven generating plant, Quirk's Victory Light Co.

The windgenerator was developed to feed batteries for remote relay stations in Australia. Around 1965 the generator attained the main design features it has today. Probably hundreds of these machines have been sold in the last decades and are operating in various places in the world. The machine has three aluminium blades that are feathered to protect the machine in high winds. This feathering is caused by the centrifugal action of governor weights against the tension of a centre spring and dampers.

The generator is coupled to the propellor via a transmission with ratio 5 : 1. Generator and transmission are built into one housing.

The generator is a 8-poled brushless 3-phase synchronous electric machine, the output current being rectified in the generator itself by Silicon diodes. The field is excited by a small auxiliary generator, mounted on the same shaft in the same housing as the main generator, thus avoiding the use of brushes. This auxiliary generator is also a small 3-phase generator, of which, however, the excitation field is situated in the stator and the 3-phase windings are in the rotor.

When wind rotor and generator start turning, a voltage is immediately excited in the field supply winding as a result of residual magnetism. When this voltage exceeds approx. 50 V, the regulator admits current to flow to the field excitation of the auxiliary generator. The current excited in the phase windings of the auxiliary generator is rectified and transmitted to the field excitation winding of the main generator. See fig. 2. The generator voltage can now rise quickly to the value set by the regulator.
This regulated voltage can be adjusted from 95 to 140 Volts by a potentiometer. The regulator operates by switching the field current on and off. The technical drawings of generator and regulator are given in fig. 3.
The regulator is housed in a cubicle, that should be placed as close as possible to the batteries. The generator output leads and control lead pass through 3 sliprings inside the turntable. The diameter of the connecting cables should be large to limit the voltage drop.
As stated before, the machine is designed to charge batteries; these batteries can, according to the manufacturer, supply a continuous load of up to 500 Watts, depending on the average windspeed.
The tower is of a three-post construction and can be supplied in 10 ft. multiples from 10 to 70 ft. high.
The generator is equipped with a mechanical brake on the propellor shaft, that can be operated from ground level.
The generator is directed to the wind by means of a tail vane.
3. TEST SITE AND INSTALLATION

The windgenerator was installed and tested on the flat roof of the High Speed Laboratory Building of the Physics Department. Figures 4 and 5 show the situation.

Only the top section of the tower was used, in all 6.70 m, resulting in a height of the rotor shaft above ground level of approximately 17 m. Although the site is reasonably open to the prevailing south-west wind direction, the turbulence level is very high due to the buildings of Eindhoven city centre at approximately 1 km distance.

A few modifications were made to facilitate the installation and repair of measuring equipment. The tower footing was equipped with a hinge, so that the whole tower can be lowered or raised with the aid of two winches as shown in fig. 6.

The blade arm castings broke when installed according to the installation instructions; they were replaced by three new ones made of steel.

The struts on which the platform is mounted, were too long, viz. the blades in fully feathered position could touch the platform. A smaller platform has been made.

The clamps that tighten the generator to the head were not able to prevent movements of the generator. Additional strips were mounted between the clamps.

Problems arose, too, while building the tower. Girts and stays had to be adjusted before they could be fitted between the posts and main angle irons.

The ladder couldn't be placed inside the tower; with additional lengths of pipe it was bolted at the outside.

After some time it became clear that this type of machine at present is normally fitted with magnetic latches for the feathering systems. As the machine that was delivered for
testing did not have these latches, it is presumed to be of an older type. The delivered manual, however, was of the new type, which gave rise to much confusion about the required torque of the centre spring.
4. MEASUREMENTS

4.1. Introduction

Quantities that describe the behaviour of a wind energy system are:

- the tip speed ratio $\lambda$, defined as $\lambda = \frac{\Omega R}{V}$
  in which
  $\lambda$ is the tip speed ratio (-)
  $\Omega$ is the angular velocity (rads/sec)
  $R$ is the rotor radius (m)
  $V$ is the windspeed (ms$^{-1}$)

- the power coefficient of the rotor, $c_p$, defined as $c_p = \frac{P_r}{\frac{1}{2}\rho\pi R^2 V^3}$
  in which
  $c_p$ is the power coefficient (-)
  $P_r$ is the rotor shaft power (W)
  $\rho$ is the air density (kgm$^{-3}$)
  $V$ is the mean windspeed (ms$^{-1}$)

- the total system efficiency, $\eta$, defined as $\eta = \frac{P_e}{\frac{1}{2}\rho\pi R^2 V^3}$
  in which $P_e$ is the power consumed by the electrical load, and the denominator equals the power in the wind flowing through the rotor plane.

Hence, the quantities to be measured for describing the performance of the windgenerator are: windspeed $V$, rotational speed of the rotor $\Omega$ (= 2$\pi n$), position of the rotor head $\phi_h$, wind direction $\phi_v$, electric voltage $V_e$, electric current $I_e$, and/or electric power $P_e$. (Note: $\phi_h - \phi_v = \theta$)

The total efficiency can be written as $\eta = c_p \cdot \eta_{tr} \cdot \eta_{me} \cdot \eta_{tp} \cdot \eta_{st} \cdot \eta_{reg}$, in which (see also below)

$c_p$ is the power coefficient of the rotor
$\eta_{tr}$ is the efficiency of the mechanical transmission
$\eta_{me}$ is the efficiency of the generator
$\eta_{tp}$ is the efficiency of the electrical transmission through the cables
\[ \eta_{st} \] is the storage efficiency
\[ \eta_{reg} \] is the regulator efficiency

a) aerodynamic losses; it is impossible to convert the total amount of kinetic energy of the wind into mechanical energy. Theoretically a maximum \( c_p \) can be obtained of 0.593 (Betz limit). In windtunnel measurements on rotor models \( c_p \)'s of 0.40 to 0.50 have been found. In open tests stands, however, extra losses (due to yawing of the rotor with respect to wind direction, to wind shear and to wind turbulence) are involved.

b) electrical losses in the generator.
Note: losses under a) and b) are influenced by the way of matching the rotor to the generator.

c) mechanical transmission losses in the gearbox, the bearings and the generator.

d) transport losses in connecting cables; these were negligible by using extra thick (8 \text{ mm}^2) cables during the measurements.

e) storage losses in batteries.

f) losses due to the way in which the voltage regulator works.
As the regulated voltage is fixed, the charge current is limited, depending on the load-state and capacity of the batteries, and of course on the regulated voltage value itself. We will come back to this later. Further, the system only delivers power when the rotor speed is high enough to produce the required generator voltage.

4.2. Measuring equipment

Some quantities were measured as analog signals, others as digital signals that, if necessary, could be converted into analog signals also. Up to six signals could be recorded simultaneously on a six-channel x-t recorder (Example see fig. 7). The experimental set-up for all measurements is shown in fig. 9.

Windspeed

The windspeed was measured with the aid of so-called pipo-anemometers with three cups made of table tennis balls. These
anemometers, that were developed by the Wind Energy Group, give electric pulses (24 per revolution) that in number are linearly proportional to the windrun. The pulses were counted with the aid of a digital pulse counter and additionally shown on an analogue display. A typical calibration curve is shown in fig. 8. With some measurements two anemometers were used, both placed in the rotor plane, one half a meter above and the other half a meter below the rotor. The procedure in which the two signals are averaged to determine the windspeed has been discussed in [8]. For other measurements only the top anemometer was used.

**Rotational speed**

A plate with 360 slots was mounted on the rotor axis; the number of slots passing a photocell in a certain time is a direct measure of the rotational speed. The digital signal could be transformed into an analog signal.

**Wind direction and position of rotor head**

These were measured with potentiometers, the voltage generated being proportional to the difference in angle with some reference value.

**Electric current**

The generator current was led through a calibrated Kanthal wire, resulting in a voltage drop that could be recorded on the x-t recorder or a Wattmeter.

**Electric voltage**

The generator output voltage was recorded by the x-t recorder or fed into the Wattmeter.

**Electric power**

The output power of the generator was measured in series I by multiplying voltage and current (with the regulator on), in series II by multiplying the square of the current with the number of ohms of the resistive load (with the regulator off) and in series III and IV by using a Wattmeter; both input signals
(voltage and current) may vary continuously. The Wattmeter was built by Eep van Voorhuisen, of our laboratory.

4.3. Measurements

4.3.1. Series I [2]

This series was done with a resistive load and the regulator switched on. This meant that the current could not exceed the value determined by the load resistance and the set value of the regulator, thus limiting the power output.

These measurements were used to control and evaluate the measuring system, but were unsuited to obtain meaningful performance data.

4.3.2. Series II [3]

This series was done with a resistive load but with the regulator switched off, so any amount of power could be delivered (and measured). From recorder registrations those intervals were chosen where all signals remain more or less constant. Thus, these series resemble windtunnel conditions and the measurements can be compared with the windtunnel measurements on rotor and generator reported by Hinsley and Smith [7].

In evaluating the data, 30 intervals of 3 to 16 seconds duration were selected out of continuous registrations lasting in all 2 hours (see fig. 7). Criteria for selection of these intervals are treated in detail in [3], one being, for example, that the angle of yaw remained less than 25 degrees. Fig. 10 shows the results of this series ($c_{p} n_{tr} n_{me}$ versus windspeed) compared to the windtunnel measurements of [7].

4.3.3. Series III [4, 5]

The machine was connected to 9 batteries of 12 V, 60 Ah, with the voltage regulator set at 121.5 Volts, which meant a charging voltage of 13.5 Volts per battery.

The windspeed and the power output were measured during two periods of one hour; the readings were recorded every five minutes. In
the first run the centrifugal weights were free to operate in the normal manner. In the second run they were fixed in the starting position. Results are shown in fig. 11.

4.3.4. Series IV [5]

The machine charged 8 batteries, with the voltage regulator set at 128 Volts; thus the charging voltage per battery was 16 Volts. This permitted a much higher charging current without increasing the capacity of the batteries. However, the charge state of the batteries had to be checked regularly to avoid gassing.

This series was done with the centrifugal weights out of operation.

Fig. 12 gives the results of this series: total system efficiency $\eta$ against $\lambda$ (of course with $\eta_{st} = 1$). Also the results of series II are shown in this figure.

Figure 13 compares the results of series IV (power output versus windspeed) with those measured at the well exposed Bohus Malmö site [6]; the latter were measured as averages over a one month period.
5. DISCUSSION OF RESULTS

5.1. Rotor and generator

The measured $c_p \cdot \eta_{tr} \cdot \eta_{me}$ values of series II (fig. 10) fit fairly well to the windtunnel measurements of [7]. At present $c_p \cdot \eta_{tr} \cdot \eta_{me}$ values for a windgenerator can be possible of the order of magnitude 0.30 to 0.40. The Dunlite machine shows values well below this.

Fig. 12 (series II and IV) shows that the machine has an optimal $\lambda$ of 3 to 4. The blade solidity (and number of blades) of the machine suggests an optimal $\lambda$ of 5 to 6. See fig. 14 and 15 (blade solidity of the machine = 0.10). This difference is probably caused by an incorrect aerodynamic lay-out of the rotor, or by an improper matching of the rotor and the generator, or by a combination of these effects.

The blades have a more or less triangle profile, of which lift and drag characteristics are unknown, but are expected to be rather poor. (See fig. 16.) It is intended to test a profile model in the windtunnel to obtain the aforementioned characteristics. Furthermore it is intended to measure the torque vs. speed curves of the generator on a laboratory test stand. It is expected that these measurements will clarify the low efficiency of the Dunlite machine.

These measurements may also help to explain the starting properties of the machine. It was observed that the rotor starts turning at a wind speed of 6 ms$^{-1}$; once turning, it remains to do so until the wind speed drops below 4 ms$^{-1}$. It starts delivering power to the batteries at approx. 7 ms$^{-1}$. The manufacturer mentions a cut-in windspeed of 4.5 ms$^{-1}$ (10 mph), not clarifying whether this is the starting windspeed of turning of the rotor or the starting windspeed of power delivery. It is clear, however, that the measured machine does not meet either of these specifications.

Fig. 11 clearly shows that due to the improper functioning of the safety system, energy is wasted over a wide range of windspeeds. This trend is also noticeable in fig. 10, where for $\overline{V} > 8$ ms$^{-1}$.
our measurements are below those of [7].

In fig. 13 the results of series IV and those of Bohus Malmö [6] are presented together. They can be compared with each other with respect to the safety system, because the Bohus Malmö machine has magnets that prevent the motion of the centrifugal weights up to a wind speed of 9 m s\(^{-1}\). The differences between Eindhoven and Bohus Malmö measurements stem from the different time period of averaging (five minutes in Eindhoven, one month in Bohus Malmö) and from the fact that the Eindhoven site is very turbulent compared to the Bohus Malmö site. Regarding the former effect, it should be noted that the total energy in the wind over a period of one month can be up to twice as high as the energy in the wind calculated on the basis of the average wind velocity in that period. The high turbulence causes extra energy losses due to excessive yawing, etc.

The highest total system efficiency measured at the Eindhoven test site is slightly more than 0.10, when the safety system was out of operation. The total efficiency is substantially lower when the safety system is in operation (see fig. 11). Some loss in efficiency certainly is due to the bad Eindhoven site conditions, but from fig. 13 it can be derived that even at a good site (Bohus Malmö), \(\eta\) does not exceed 0.19. A properly designed, electricity generating windmill can work at a total system efficiency of say 0.30.

5.2. **Voltage regulator**

As mentioned before, the regulator keeps the generator voltage at a manually adjustable value. Although this is common practice for battery-charging systems, in the case of a windmill system it has some severe drawbacks.

Firstly, the batteries should be protected against total discharge. Sound operation requires that the load state of the batteries is kept above 25% of full load. This machine lacks
such a device; neither does the manufacturer indicate what maximum continuous load can be supplied by the batteries, as a function of the average windspeed at the site.

Secondly, in order to prevent the batteries from the gassing state, the charging voltage per battery should not exceed 14 V. This same value, however, limits the charging current and thus the power that can be delivered to the batteries. This effect can be diminished by increasing the battery-capacity, but this raises the costs. It is better to apply a higher charging voltage (16 V) when the load state of the batteries is lower then 80% of full load, and to automatically diminish the charging voltage to 14 V in the upper region of the load state. It should be noted, however, that a higher charging voltage can diminish the life time of the batteries.

In conclusion it can be said, that a regulator for a battery charging windgenerator should be designed taking into account the power output of the generator, the installed capacity of the batteries and their life time.

5.3. Rated power

The Dunlite machine reaches its rated power at approx. 11 ms\(^{-1}\), according to the manufacturer. In general it seems advisable to choose the rated windspeed about a factor 1.5 to 2 higher than the average windspeed at the site. The lower value leads to a better availability of the energy yield, the higher value to a higher (total) energy output, but somewhat lower availability.

In charging batteries the availability of the energy yield is usually more important than the total energy output; so a rated windspeed of 1.5 times the average windspeed is advisable. This means that with a rated windspeed of 11 ms\(^{-1}\), the Dunlite is suited for sites with average windspeeds of 7 ms\(^{-1}\) and higher. Sites with such windspeeds are rather rare.
6. CONCLUSIONS

1. The 2 kW Dunlite machine has been designed for sites with high average windspeeds ($\bar{V} > 7 \text{ ms}^{-1}$). For sites with lower windspeeds the machine is hardly appropriate.

2. From rotor design theory the machine is expected to have an optimal $\lambda$ of 5 to 6 (based on number of blades and blade solidity). The measurements in Eindhoven, however, reveal an optimal $\lambda$ of 3 to 4.

3. From an aerodynamic point of view the blade profile appears to be uncommon; the aerodynamic properties (lift vs. drag), although not measured, are expected to be rather poor.

4. The measured cut-in windspeed (i.e. rotor starting windspeed or power starting windspeed) is above that mentioned by the manufacturer.

5. The measured overall efficiency of the machine is a factor 1.5 to 2 below that which is technologically feasible at present.

6. The safety system (feathering of the blades) comes into operation at too low windspeeds, thus diminishing the energy output.

7. The voltage regulator, though simple and reliable, does not fully provide an adequate matching of the windmill output to the specific characteristics of a battery storage.

8. The tower and head of the machine are of a firm, reliable construction. The safety system operated without any failure.

9. In most aspects the manual is quite detailed, but lacks some important information; for instance about the continuous load that the systems can supply at different wind regimes.

Recommendation:

It seems worth while to fit an aerodynamically efficient rotor of a larger diameter with an appropriate transmission to the existing generator, expecting much higher $c_p \cdot \eta_{tr} \cdot \eta_{me}$ values.
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- analogue display
- pulse counter

- transmission
- auxiliary generator
- main generator

- voltage regulator

- Wh meter

- S1
- S2
Figure 10. Results of series II compared with windtunnel measurements of Hinsley and Smith.
Figure 11. Results of series III.
2 KW BRUSHLESS WIND DRIVEN POWER PLANT

Case No. 1 OF 1 contains:

✓ 1 only 440 V. Brushless Generator, Serial No. W50325.
✓ 4 only Generator Brackets c/w Bolts, Nuts & Washers
✓ 1 only Link Rod c/w Nuts & Washers
✓ 1 only Centre Pullout Rod. Measurements: 78x50x56 cm. Weight: 136 Kilos Gross.

Case No. 2 OF 1 contains:

✓ 1 only Head Assembly Serial No. E749. Measurements: 39x36x46 cm. Weight: 39 Kilos Gross.

Case No. 3 OF 1 contains:

✓ 1 only Variable Pitch Propellor Hub. Serial No. F2803.
✓ 1 only Aluminium Hub Cap
✓ 1 only Diotran Control Board, Serial No. C40577
✓ 1 only Front Tailrib c/w U Bolt & Nuts
✓ 1 only Back Tailrib c/w U Bolt & Nuts
✓ 1 only Pair Tailwings
✓ 1 only Set Tail Bolts & Nuts
✓ 1 only Brake Lever Assembly Measurements: 96x63x45 cm. Weight: 68 Kilos Gross.

Case No. 4 OF 1 contains:

✓ 3 only Propeller Blades c/w Stub Arms, Serial No. F2503.
✓ 3 only Governor Weights c/w Nuts
✓ 1 only Tail Bone c/w Suspension Angle & Bolt

Measurements: 220x37x22 cm. Weight: 52 Kilos Gross.

MARKS:

CONSIGNMENT:

VESSEL:

ENERGY SYSTEMS
PHILIPS
EIND HOVEN.
VIA ROTTERDAM.

ANNEX I
Figure 15. Solidity ratio for optimum performance [9]
Figure 16. Effect of $C_D/C_L$ for three-bladed rotor.[10]