DOE/R4/10249--T1

10249

DOE/R4/10249--T1

DE84 000375

Final Report
AN IMPROVED GENERATOR
FOR USE WITH
LOW-SPEED
ROTATING MACHINES

By Jerry W. Goerz

KY-20

FB44-80R410249

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE.
It has been reproduced from the best
available copy to permit the broadest
possible availability.

MASTER

JHG
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

FINAL REPORT

AN IMPROVED GENERATOR FOR USE WITH LOW-SPEED ROTATING MACHINES

An experiment conducted
under the auspices of
The Department of Energy
Appropriate Technology Small Grants Program

Grantee: Jerry W. Goerz

Grant Number: DE-FG4480R410249.000

Report Date: March 31, 1983

AN IMPROVED GENERATOR
FOR USE WITH
LOW-SPEED
ROTATING MACHINES .

TABLE OF CONTENTS

Page 2:	Overview
Page 3:	General Description of Mechanism
Page 4:	Detailed Description of Magnets
Page 5:	Detailed Description of Coils
Page 6:	Detailed Description of Coil Frame
Page 7:	Detailed Description of Rectifier Circuitry
Page 8:	Schematic of Rectifier Circuitry
Page 9:	Detailed Description of Windmill Frame
Page 10:	Detailed Description of Blade Assembly
Page 11:	Description of Related Equipment
Page 12:	Typical Output Data
Page 13:	Performance of Mechanism
Page 14:	Identification of Fundamental Design Problems
Page 15:	Similar Work by Others

Overview:

The goal of this project was to construct a low-technology, maintenance-free DC electrical generator suited for use with low-speed rotating machines such as windmills or waterwheels. The generator consists of permanent magnets affixed to the circumference of the rotating device, and stationary coils mounted on a semicircular frame. As the device rotates, the magnets move past the coils and magnetically induce an AC voltage in the coils. This voltage is rectified and stored in a battery. No gears, belts, or brushes are used, so the generator operates quietly and without maintenance. The purpose of mounting the magnets at the circumference of the rotating device is to achieve high relative velocities between magnets and coils even at slow rotations, in the hope of extracting energy from very light winds or slowly flowing water.

Such a generator was constructed as part of a ten-foot-diameter windmill to test the concept. The generator easily reaches charging voltages at low speeds, and operates quietly without mechanical wear. But the charging current is very low in comparison to a wind turbine of conventional design. The experiment allows fundamental design problems to be identified at the conclusion of this report.

General Description of Mechanism:

Eight permanent magnets were mounted on adjustable sleeves at the tips of eight windmill blades. 48 coils were mounted on an adjustable semicircular frame below the blade. The coils were wired in pairs to 24 rectifiers, and the outputs of the rectifiers were summed in series-parallel fashion using filter capacitors. The windmill is an upwind design with a downwind tail steering the windmill to face the wind. No overspeed protection device is used because the magnets at the blade tips have enough aerodynamic drag to serve as overspeed brakes.

Detailed Description of Coils:

Forty-eight coils are mounted in two parallel 24-coil arcs. The coils were removed from 110-volt AC solenoids, Jerryco No. AX-1210-1. The coils have a DC resistance of 44.4 ohms. Since the permanent magnets move over two coils simultaneously, each pair of coils is wired in series to sum their voltages. The outputs of the 24 coil pairs are wired into cables which plug into the rectifier circuitry.

To direct the magnetic flux through the coils, 9/16-by-3/8-inch laminated iron cores (formerly the solenoid armatures) are clamped to curved steel bars. The coils then fit over the cores. The coils are positioned so that one pair of coils is beneath one pole of a permanent magnet while an adjacent coil pair is beneath the other pole. Thus the magnetic flux is directed through the cores of one coil pair, through short segments of two steel bars, and returns to the magnet through the cores of an adjacent coil pair.

The curved steel bars were formed by cutting kerfs into twelve-inch-long 3/4-inch-square steel bars, and sledge-hammering the bars into the proper arc upon an anvil. The radius of the arc was compared to a cardboard template. To make the template, the distance from the blade tip to the center hub was measured and a cord of this length was used as a compass.

Detailed Description of Coil Frame:

The six curved steel bars, which support the iron cores of the coils and form a magnetic flux path, are mounted in three pairs on an adjustable framework of aluminum and wood. Each pair of curved steel bars may be moved forward or backward on sliding wooden dowels. Either end of each pair of bars may be raised or lowered by repositioning the slotted Masonite supports through which the dowels slide. The slotted supports clamp to a frame constructed of square aluminum stock. The frame pivots so that the elevation and pitch may be changed by adjusting turnbuckles which alter the length of supporting cables. The various adjustments permit the coils to be aligned under the rotating magnets. Photographs of the coil frame follow:

Detailed Description of Rectifier Circuitry:

Twenty-four Radio-Shack No. 274-1161 one-amp 50-volt bridge rectifiers and seven 1000-microfarad 50-volt electrolytic filter capacitors are wired in series-parallel fashion within the rectifier box. The coils are cabled to DIP-plugs in three groups (A,B,C) of eight pairs (pairs 1-8, each with coils "a" and "b").

Each coil pair is wired to one rectifier. The four rectified outputs of every sixth coil pair are wired in parallel to one of six filter capacitors. The six capacitors are wired in series across a seventh filter capacitor. In this manner, the voltages and currents of the coils are summed to provide an output suitable for charging a battery. Photographs and a schematic diagram follow:

group A1/A7/B5/C3

a b Coil Designations

☐	☐	1
☐	☐	2
☐	☐	3
☐	☐	4
☐	☐	5
☐	☐	6
☐	☐	7
☐	☐	8

A

☐	☐	1
☐	☐	2
☐	☐	3
☐	☐	4
☐	☐	5
☐	☐	6
☐	☐	7
☐	☐	8

B

☐	☐	1
☐	☐	2
☐	☐	3
☐	☐	4
☐	☐	5
☐	☐	6
☐	☐	7
☐	☐	8

C

DIP sockets A, B, C

DIP pin	coil pair	DIP pin
1	1	16
2	2	15
3	3	14
4	4	13
5	5	12
6	6	11
7	7	10
8	8	9

group A3/B1/B7/C5

group A5/B3/C1/C7

group A2/A8/B6/C4

group A4/B2/B8/C6

group A6/B4/C2/C8

Detailed Description of Windmill Frame:

The blade assembly, coil frame assembly, tail assembly and rectifier box all clamp to a length of PVC pipe. The inner diameter of this pipe is 1.5 inch, and the wall is 3/16-inch thick. Inside this pipe, near its top, is a greased thrust bushing. The entire windmill rests on this bushing, which in turn rests upon a steel mast. For experiments at ground level, this mast is set in concrete, but the windmill can be mounted on a tower. During high winds, the bending moment at the base of the windmill is great enough to bend the steel mast, so it is reinforced by placing another steel pipe within it and pouring concrete into the mast.

Thrust Bushing

drawn to scale

Detailed Description of Blade Assembly:

The ten-foot-diameter blade assembly is constructed of eight 58-inch lengths of 1.25-inch-diameter 1/16-inch wall aluminum tubing bolted to a hub constructed of two 12-inch-square 3/16-inch thick aluminum plates and two 4-inch-diameter ball-bearing garage-door sheaves (Torch Products No. SY-501). The ball-bearing sheaves rotate on a 3/8-inch hardened steel bolt. This bolt is supported near the bearing by a brace clamped to the PVC pipe, and the bolt passes through the PVC pipe.

Two 12-by-20-inch sheets of aluminum are shaped into curved blades which are clamped to each of the eight tubular arms. Magnets are fastened to the ends of the eight arms with adjustable sleeves. All components of the blade assembly, except for the sheaves and hub bolt, consist of aluminum, brass, and PVC, to eliminate rusting. Special care was taken wherever steel and aluminum are joined to separate these metals with brass or plastic hardware to prevent galvanic action from eroding the metals. Photographs of the blade assembly follow:

Description of Related Equipment:

An outdoor battery box holding four 12-volt parallel-wired marine batteries was constructed for storing the electricity generated by the windmill. Twelve-volt outlets and light fixtures were wired to the batteries to permit useful discharging. Meters were installed for monitoring battery voltage and charge and discharge currents.

A tower was set in concrete for the eventual permanent mounting of the completed windmill. This windmill cannot be left operating unattended at ground level, because the whirling blades tipped with heavy jagged-edged magnets pose a danger to the unwary. Despite the gyroscopic effect of a rapidly spinning blade, this windmill can turn suddenly as the wind shifts, and a person within a five-foot radius of the central support can be injured.

For experiments, wires are attached to binding posts beneath the rectifier box. For permanent mounting on a tower, the output would pass through a slip-ring assembly which would be fastened to the lower portion of the PVC central support pipe.

Typical Output Data:

Test date: March 27, 1983

Wind: average windspeed approximately 10 mph with gusts to over 20.

Windmill open circuit output voltage: 45 volts reached in average wind, 50 volts reached following gusts. (The maximum output voltage remains present after the gusts with no load attached, because the filter capacitors store this charge for a very long period, discharging only through capacitor and rectifier leakage currents.)

Windmill short-circuit current: 15 milliamps in average wind

Windmill peak output (during gusts) with various resistive loads:

RESISTANCE	VOLTAGE	OUTPUT in milliwatts
26 ohms	0.4	6.15
113 ohms	1.5	19.9
1069 ohms	8.5	67.6
12.55K ohms	48.	183.6
99.3K ohms	50.	25.2

Notes:

Resistance was measured.

Voltage was measured.

Output Power was calculated as $(V^2) / R$.

Windmill output into 13.6-volt battery:

10 milliamps (136 milliwatts) during average wind

12 milliamps (163 milliwatts) during gusts

Note: Power = Voltage x Current

This data indicates that the generator has an equivalent output impedance of approximately 10K-ohms, at which a matched load allows maximum power transfer. Charging a battery requires that the output voltage slightly exceed the battery float voltage, at which point the maximum charging current flows restricted only by the internal resistances of the generator and battery. Charging a battery with more cells, such as a 24 or 36-volt battery, would result in a larger peak power output (up to about 1/3 watt), when the windspeed permits this voltage to be reached. Aerodynamic drag appears to limit the speed of the windmill, thus limiting the maximum output voltage to about 50 volts.

Performance of Mechanism:

The useful wind power P in Watts available for extraction from a wind of speed V miles per hour by a windmill of diameter D feet is expressed by: $P=0.0024(D^2)(V^3)$ (from Harnessing the Wind for Home Energy, Dermot McGuigan, Garden Way Associates, Inc., 1978, page 15).

The wind power available for extraction by a ten-foot-diameter windmill in a 10-mph wind is thus 240 watts. In a 25 mph wind, 1500 watts is available. These figures do not account for the inefficiencies of rotors, geartrains, and generators, which together commonly permit only about 50% of the available energy to be extracted.

An assumption that 50% efficiency could be achieved was the basis for the project goal of generating 3 KWH per day in an average windspeed of 10 mph with a 10-foot-diameter windmill. This equates to a power output of 125 watts in a 10 mph wind. But in fact, the experimental windmill came nowhere near such off-the-shelf performance. The power output in a windspeed of approximately 10 mph was measured as 136 milliwatts, when charging a battery at 13.6 volts.

The possibility that magnetic saturation of the coil cores was responsible for the low output was dismissed after an oscilloscope was used to examine the voltage waveform of an unloaded coil pair. The waveform varied smoothly, revealing no saturation. Of course, when connected to rectifiers, the waveform shows discontinuities where the rectifiers conduct at about 0.6 volts, with the waveform resembling a square-wave, as expected.

With magnetic saturation ruled out, and barring wiring errors, the remaining explanations for the poor performance include insufficient magnetic flux density or insufficient rate of change of magnetic flux density.

The magnetic flux density can be strengthened by use of more powerful magnets, and by reducing the air gap between magnets and coil cores. More powerful magnets, such as rare-earth cobalt magnets, are available, but they are expensive. The air gap between magnets and coil cores is about 1/2 inch and cannot be further reduced in this particular experiment because the windmill frame lacks the rigidity needed to overcome the greater attractive forces between magnets and coil cores with narrower gaps.

The rate of change of magnetic flux density could be improved by use of a larger-diameter blade assembly, increasing the relative velocity between magnets and coils, or by achieving higher rotational velocities with the present blade assembly. A ten-foot-diameter windmill is about all one experimenter can safely handle. Improved blade design could increase the windmill speed somewhat, but the most speed increase would come from streamlining the magnet assemblies.

Identification of Fundamental Design Problems:

This project demonstrated that the design of a large-diameter brushless generator with magnetic couplings at the circumference presents fundamental design problems. In order to avoid the wear of brushes, permanent magnets served as the source of magnetic flux. But permanent magnets are weak in comparison to electrically energized magnets. To strengthen the field, large and heavy permanent magnets were used. Such large and heavy magnets mounted at the circumference of the windmill led to problems with aerodynamic drag and large centrifugal forces. Much time was required to develop an adjustable magnet mount which would not rip apart in service, as did early versions.

Exploiting a weak magnetic field requires close proximity between permanent magnets and coils. When the magnets are mounted at the circumference, any mechanical looseness at the hub translates to substantial misalignment at the rim. Hindsight shows that garage door sheaves on a 3/8-inch bolt made an inadequate hub bearing. In operation, the blade assembly wobbles enough to cause misalignments of about four inches at the rim. This meant that the magnets were sometimes not passing over one of the two rows of coils.

Insufficient structural rigidity of the windmill frame and adjustable coil frame made it impossible to allow the magnets to come closer than about 1/2-inch to the coils. Any closer, and the framework would yield to the magnetic attraction, the magnets would contact the coils, and the windmill would come to a screeching halt.

For mechanical tolerances to be tightened, the blade assembly should be supported by a long, thick axle supported at each end by roller bearings. The frame supporting the coils should be very rigid, probably not adjustable but instead constructed to very close tolerances from the outset. A large and rigid windmill frame would be needed to permit the magnets to come within hundredths of an inch of the coils, yet resist magnetic attraction and prevent contact. Such a rigid framework likely could not be supported on one mast, and could not easily be constructed to point into the wind.

The challenge of such a construction makes the drawbacks of conventional, compact, high-speed, electrically-excited generators appear trivial, regardless of brush wear.

Similar Work by Others:

When this project was conceived, wind turbines were just regaining favor after decades of disinterest. Many or all of the available windmills were high-speed, noisy machines requiring frequent maintenance. Such machines often used automotive generators driven by gears or belts. Since that time, much progress has been made by private industry toward perfecting gearless, brushless wind turbines. For example, the Bersey BWC-650 and BWC-1000 wind turbines incorporate a "low-speed alternator, which uses multiple sets of stators and magnet rings to eliminate field windings, commutators, and brushes," which "allows the alternator to be driven directly by the blades, without the usual step-up gearing." (Popular Science, June 1982, page 114) The Bersey machines may be described generically as direct-drive permanent-magnet-alternators. The permanent magnets are incorporated into a compact generator directly behind the blade hub. Because the magnets are mounted near the hub and not at the blade tips, the problems of mechanical tolerances, centrifugal forces and aerodynamic drag are eliminated.

A recent study reveals six manufacturers of direct-drive permanent-magnet-alternator wind turbines. (Popular Science, July 1982, page 55) The manufacturers and their machines are:

MANUFACTURER -----	MODEL -----	KW RATING -----
Bersey Windpower	1000-S	1.0
Bertoia Studio	A.P.S./H	2.0
Whirlwind Power	3000	3.0
Windstar	WS-462-16	4.0
Windworks	Windworker 10	9.0
Zephyr Wind Dynamo	Windtilter	0.5