NREL/TP-441-6626 • UC Category: 261 • DE94006930

Wind/Hybrid Power System Test Facilities in the United States and Canada

H. J. Green, R. N. Clark, C. Brothers, B. Saulnier

Prepared for
WindPower 94
May 9–13, 1994
Minneapolis, Minnesota

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Operated by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC02-83CH10093

Prepared under Task No. WE437310

May 1994

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling (423) 576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

Printed on paper containing at least 50% wastepaper, including 10% postconsumer waste

WIND/HYBRID POWER SYSTEM TEST FACILITIES IN THE UNITED STATES AND CANADA

H. James Green, National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado, 80401 USA

R. Nolan Clark, USDA Conservation and Production Research Laboratory
P.O. Drawer 10, Bushland, Texas, 79012 USA

Carl Brothers, Atlantic Wind Test Site
North Cape, Prince Edward Island, C0B 2B0 Canada

Bernard Saulnier, Institut de Recherche d'Hydro-Quebec
1800 Montee St. Julie, Varennes, Quebec, J3X 1S1 Canada

INTRODUCTION

By 1995, there will be four facilities available for testing of wind/hybrid power systems in the United States and Canada. This paper describes the mission, approach, capabilities, and status of activity at each of these facilities. These facilities have in common a focus on power systems for remote, off-grid locations that include wind energy. At the same time, these facilities have diverse, yet complimentary, missions that range from research to technology development to testing.

The first facility is the test facility at the Institut de Recherche d'Hydro-Quebec (IREQ), Hydro-Quebec's research institute near Montreal, Canada. This facility, not currently in operation, was used for initial experiments demonstrating the dynamic stability of a high penetration, no-storage wind/diesel (HPNSWD) concept. The second facility is located at the Atlantic Wind Test Site (AWTS) on Prince Edward Island, Canada, where testing of the HPNSWD concept developed by Hydro-Quebec is currently underway. The third is the Hybrid Power Test Facility planned for the National Wind Technology Center at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, which will focus on testing commercially available hybrid power systems. The fourth is the U.S. Department of Agriculture (USDA) Conservation and Production Research Laboratory in Bushland, Texas, where a test laboratory is being developed to study wind-energy penetration and control strategies for wind/hybrid systems.

The authors recognize that this summary of test facilities is not all inclusive; for example, at least one U.S. industrial facility is currently testing a hybrid power system. Our intent, though, is to describe four facilities owned by nonprofit or governmental institutions in North America that are or will be available for ongoing development of wind/hybrid power systems.

HYDRO-QUEBEC WIND/DIESEL TEST FACILITY

Background—The wind/diesel program of IREQ, Hydro-Quebec's research institute, aims at reducing the cost of electricity production in 14 villages of northern Quebec and 5 communities along the North Shore of the St. Lawrence River. These communities are supplied with electricity produced by diesel gensets. The peak demand for each community ranges from about 180 kW to 6000 kW, with a total demand of about 22 MW.

A 1986 technoeconomic study [1] identified the HPNSWD scenario as the most promising because of its relative simplicity and economic advantages. It gives priority to wind energy (free fuel) and allows the diesel gensets (expensive fuel) to be shut down when the winds are strong enough to supply all the electric power required by the network. The scenario is particularly well adapted where excess energy can be put to profitable use like displacing fuel used for space heating in Quebec's remote communities.

Mission—To provide an experimental demonstration of the dynamic stability of the HPNSWD scenario at Hydro-Quebec's Research Institute.

Objectives—The four primary objectives are the following:

- Allow the demonstration, without the use of storage, of the dynamic stability of a small remote grid where a varying demand is fed by a variable source of energy like wind.
- Demonstrate that a frequency regulator can control the value of dispatchable loads to maintain the difference between production (diesel plus wind) and demand (consumer plus dispatchable) to zero.
- Develop tools for the design of a frequency regulator.
- Develop an understanding of the dynamics of the HPNSWD and the influence of the frequency regulator characteristics on its stability.

Technical Approach—The approach includes five activities:

- Model the HPNSWD system with the EMTP (Electromagnetic Transient Program).
- Measure the parameters of the main subsystems to incorporate in the model. Measurements include inertias, electrical parameters (resistance, reactance, voltage regulator), and diesel-speed regulator response time.
- Monitor current, line voltage, frequency, diesel rpm, and instantaneous power transducer signals.
- Measure the response of the system to large demand transients.
- Validate the simulation model with experimental data.

Facility Capabilities—The IREQ test facility has always focused on dynamic testing. The high-speed data acquisition can handle up to 32 channels. Care has been taken to ensure high-quality monitoring in this installation (high signal-to-noise ratio, insulation, and instrumentation grounding requirements). Since 1986, it has been used in the framework of Hydro-Quebec's wind/diesel activities to validate technical choices and the design of the frequency regulator. (The facility has been described previously in detail [2].)

Figure 1 shows a facility schematic, where the installation consists of the following:

- 50-kW Indal VAWT (vertical-axis wind turbine)
- 35-kW diesel genset equipped with an overrunning clutch
- 50-kW resistive load to simulate a village
- 7-step binary-progression dump load (resistive) to absorb production surplus
- High-noise-rejection, digital-filtering, high-speed, 32-channel data acquisition computer system.

Status—The dynamic stability of the HPNSWD system was demonstrated analytically in 1987 and was validated experimentally in 1990 at IREQ's test facility. The follow-on phase of the project required a village-size installation and the use of a mini wind farm to validate the control strategy for the

HPNSWD scenario. This is currently underway at the AWTS. Presently, the IREQ facility is kept operational in case further dynamic stability work is deemed necessary.

WIND/DIESEL DEVELOPMENT AND TEST FACILITY AT THE AWTS

Background—Wind/diesel applications represent one of the most significant near-term markets for wind energy in Canada. Several hundred communities—located in remote, mostly northern, areas of the country—rely on expensive diesel-powered generators for all their electrical needs. The Atlantic Wind Test Site has been investigating wind/diesel applications since the mid-1980s and currently has a fully equipped test bed capable of assessing a range of issues that will affect future wind/diesel deployment.

AWTS, located in northwestern Prince Edward Island, Canada, has a harsh climate. An aggressive marine environment coupled with high annual wind speeds, extreme winter temperatures, and frequent icing events provides an ideal environment for testing wind turbines. It also provides an excellent location for realistic simulation of wind/diesel operating strategies.

Mission—To provide a fully equipped simulation facility to fully assess the practicability of a variety of wind/diesel deployment strategies.

Objectives—The four primary objectives are the following:

- Perform performance, reliability, and operational tests on wind turbines and related equipment targeted for remote, primarily northern, community application.
- Develop and validate wind/diesel models that can be used for technical and economic analysis of wind technology options in remote communities.
- Acquire data from existing communities to provide a better understanding of the potential market.
- Assess wind/diesel operational strategies in realistic, but low risk, conditions prior to installations in remote communities.

Technical Approach—Collaboration is the key to optimizing the contribution that AWTS can make to wind/diesel development. Although AWTS possesses excellent facilities and an extremely competent operating staff, the research capabilities are limited due to the small number of staff.

Facility Capabilities—The AWTS Wind/Diesel Test Bed is currently configured with two 50-kW Volvo diesel engines driving Kato synchronous generators (1800 rpm, 600 V, 3 PH). These generators, equipped with fully automatic synchronizing equipment, provide base power to a simulated community (resistive load bank) with a peak load of 115 kW. Daily load variations in the community are controlled in a binary fashion by an independent computer at a rate of one hertz (Hz). Figure 2 shows a schematic of the facility.

Five wind turbines, with a total generating capacity of 285 kW, can be connected either to the local utility grid or to the test-facility diesel grid. The turbines include:

- 40-kW Enertech HAWT (horizontal-axis wind turbine) — fixed-speed induction generator
- 35-kW Indal VAWT — fixed-speed induction generator
- 65-kW Windmatic HAWT — two-speed induction generator
- 80-kW Lagerwey HAWT — variable-speed
- 50-kW Atlantic Orient Corporation (AOC) 15/50 HAWT—fixed-speed induction generator.

Of the turbines installed, the Lagerwey and the AOC are commercially available units currently being assessed at AWTS for deployment in the remote-community market.

With the system capable of operating at very high wind-penetration (wind power relative to diesel power) levels, a dump load is required to dissipate any wind energy provided to the system that exceeds immediate requirements. The dump load is rated at 190 kW and is switchable in 1.5-kW increments using zero-crossing solid-state switches.

For autonomous operation at high-wind power levels, the diesels can be turned off and the system frequency and voltage regulated independently. Voltage can be regulated in several ways. The synchronous generators, which are decoupled from the diesels with overrunning clutches, can remain in operation using their voltage regulators when the diesels are turned off. Synchronous condensers have also been used on the system and are fully functional. Some voltage stability can also be provided by connecting power-factor correction capacitors in steps. Frequency is usually regulated by a PID (proportional-integral-derivative) controller connected to the dump load.

The equipment is instrumented for multiple purposes. Several data acquisition systems are in use at AWTS. Long-term operating data are gathered at a 1-Hz rate and stored as 10-minute averages using Campbell Scientific Dataloggers. For higher-speed acquisition and analysis, several personal-computer(PC)-based data acquisition systems are available that can acquire data at rates higher than 1000 Hz.

Status—The AWTS test bed is fully functional with all five wind turbines operational on the system. A current 3-year collaborative program with Hydro-Quebec seeks to demonstrate the practicability of Hydro-Quebec's HPNSWD strategy. This program will conclude in early 1995, but portions of the project will remain intact for future study. The AWTS test bed is available for collaborative studies and the AWTS staff wish to discuss opportunities with any interested parties.

NREL HYBRID POWER TEST FACILITY

Background—The Hybrid Power Test Facility (HPTF) is one element of a larger effort at NREL to assist U.S. industry in developing new technology and applications for small wind and hybrid power systems. To this end, NREL is also developing hybrid power-system performance models and providing international technical assistance. These activities are funded by the U.S. Department of Energy (DOE) Wind Energy Program.

Mission—To assist U.S. industry in developing new technology and applications for small wind and hybrid power systems by developing and testing wind/hybrid power systems.

Objectives—The five primary objectives are the following:

- Install and test small wind and hybrid power systems that are near market, unproven, or under continuing development.
- Develop and test new approaches, in collaboration with industry, that will improve performance and cost effectiveness. These may include component dispatch/control, innovative components, and advanced system configurations.
- Provide a system-development user facility for U.S. industry.
- Stimulate foreign markets by providing a hands-on training facility for foreign nationals.

- Develop and test data-acquisition systems for remote monitoring of hybrid systems prior to field installation.

Technical Approach—Hybrid power systems, including wind and photovoltaics (PV) will be installed and made operational at the National Wind Technology Center (NWTC) at NREL. The NWTC is a wind-energy test site near Golden, Colorado, currently under renovation. Both real and simulated wind and PV energy sources will be provided. The simulated renewable energy sources will allow repeatable testing and testing under controlled combinations of solar and wind resources, and load banks will simulate village electric loads. When fully developed, the facility will be capable of simultaneous testing of two or more hybrid power systems.

The primary focus at this facility will be to conduct performance tests with complete systems from U.S. manufacturers. NREL will also seek opportunities to test innovative subsystems, such as flywheel energy storage or variable-speed gensets. The facility will be made available to industry users, visiting professionals, and university faculty and students. In particular, NREL has a program underway in which foreign nationals are working at NREL as visiting professionals for several months to gain experience with hybrid systems. The HPTF will give these visitors hands-on experience with the newest U.S. technology in hybrid power.

Facility Capabilities—The HPTF will include a distribution panel that provides the flexibility to rapidly reconfigure the facility (see schematic in Figure 3). This panel will be a jack panel as commonly used in electrical power laboratories. Through this panel, any of the renewable energy sources, renewable energy simulators, or village load simulators can be connected to any one of several hybrid power systems on site.

Village loads will be simulated by one or more controllable load banks with both resistive and inductive components and capacity up to 80–100 kW. A separate dump load, if appropriate for the system under test, will be provided. Initially, the renewable energy sources available at the facility will include a PV array (nominally 10 kW) and two wind turbines:

- 10-kW Bergey Excel—variable-speed, rectified direct current (DC) output
- 50-kW Atlantic Orient Corporation 15/50—fixed-speed induction generator.

The facility will include at least two renewable energy source simulators—one supplying DC and the other alternating current (AC) power. The DC source simulator will most likely be a commercially available DC motor drive. The AC drive will be an induction generator driven by a variable-speed electric motor.

The facility will have central, PC-based data acquisition and control capability including software with a graphical user interface. Test parameters to be measured will include overall energy delivery and fuel consumption, power quality, dynamic response to transient conditions, and response to simulated mechanical and electrical failures. System tests will typically include operation over the full operating envelope of the system and the exercising of all alarm and system protection functions.

Status—An initial concept for the facility has been developed and a detailed design will be completed this coming summer. Facility construction will begin late in 1994 as part of the current renovation of the NWTC at NREL. Two or three power systems are anticipated to be under test during 1995.

U.S. DEPARTMENT OF AGRICULTURE WIND/HYBRID TEST LABORATORY

Background—Electrical energy is desired in almost every farm, home, and village because of the number of applications using electricity. In remote areas such as islands, large western U.S. farms or ranches, or Alaskan fishing villages, the cost of extending electric utility lines is prohibitive. Some of the larger farms and villages have installed engine-powered electric generators, most of which are fueled by diesel. Wind power has been suggested to reduce the high cost of diesel fuel in these remote areas. Several experiments have been conducted by adding a wind turbine to the present electric generating system. In nearly all cases, the wind turbine was not sized to the expected load nor was there any attempt to schedule the load or maximize the introduction of windpower. Because of this approach, very few tests have been commercially successful, although quite a few have been technically successful.

Mission—To develop and test wind/hybrid electrical generating systems that will be reliable, cost competitive, and totally independent for use in remote and rural areas. These systems will be powered entirely by renewable fuels such as wind, solar, and vegetable oils. This effort is being funded jointly by USDA and DOE as a 5-year collaborative research project.

Objectives—The four primary objectives are the following:

- Determine the level of wind penetration and necessary control strategies for various wind/hybrid configurations using uncontrolled loads.
- Determine the stability and reliability of a wind/hybrid system with and without storage.
- Collect test data sets to verify computer simulation codes used in wind/hybrid designs.
- Evaluate and measure any accelerated wear on hybrid components (e.g., engine generators, inverters, and wind turbine controls).

Technical Approach—A wind/hybrid test laboratory with an independent generating capacity of 100 kW and a corresponding amount of varying loads will be established at the USDA-Conservation and Production Research Laboratory, in Bushland, Texas. The loads will be a combination of inductive (motors) and resistive (heaters and lights) loads. Four system configurations will be selected from the American Wind Energy Association's Standard (AWEA 10.1-1991), *Wind/Diesel Systems Architecture Guidebook* [3], and each will be examined to determine any long-term operational problems. During operation, various levels of wind penetration will be evaluated and the system will be checked for electrical stability (power quality) and any effect of short-term storage. Engine wear and operational problems of vegetable-oil-fueled gensets will be measured as part of this research program.

The first configuration to be studied will consider a simple system with no storage and with the engine running continuously (Figure 4a). A dump load will prevent the wind turbine from accelerating the grid frequency in situations with surplus wind power [4]. In some tests, the wind-energy penetration may exceed 100%, but the fuel savings should be modest because of the high specific fuel consumption of the engine at partial or no load. Small negative loads (backdriving the engine) will be allowed as well, which should improve fuel savings. Frequency control should be acceptable until the negative load reaches 30% [5].

The second configuration will include multiple engines and multiple wind turbines, plus storage (Figure 4b). The purpose of the storage is to delay or prevent the starting of a second or third engine when a short-term load spike is observed or when the wind dies for short periods. This system is anticipated to operate in a similar manner to the first configuration, but with better power quality and less probability of system failure. The penetration will again be allowed to exceed 100%, and the engines may be backdriven.

The third configuration will include a clutch and possibly a flywheel, but no storage (Figure 4c). The clutch will allow the engine to be stopped if the available wind power is sufficient to satisfy the loads. The generator continues to spin, functioning as a synchronous condenser, to supply reactive power to the induction generators on the wind turbines [6]. This system configuration provides the best fuel economy, but requires a more sophisticated control system and a dump load to keep the system in balance at all times. This configuration will be with one engine and one wind turbine to simplify the controls for operating the synchronous condenser.

The fourth configuration is similar to the third configuration, but with a storage system that will provide energy for a few hours (Figure 4d) and will include multiple engines and multiple wind turbines. Storage is added to the system to reduce the number of starts and stops of the engines and to provide longer off periods between engine run times. The greatest fuel savings should be achieved when the engines are off. This configuration may well be the optimal design for lower cost and higher reliability, but the principles and reactions of the other designs must be understood before reaching this final design.

This project will include many incremental tests that will be performed systematically as the project progresses. The results of one test will determine the steps in following tests. A penetration test will be performed in turn on each configuration; stability and reliability tests will be conducted as penetration tests are performed. In all cases, actual field operations data will be collected for predicting and designing computer simulation codes. Measuring engine performance and emissions from the vegetable fuels will be done simultaneously with other tests.

Status—The research plan for this facility is currently being defined. The facility should be operational in 1995.

COMPARING THE FOUR FACILITIES

These four facilities are each unique in their mission and approach. The IREQ test facility and the current activity at the AWTS are focused on developing a particular new technology—high penetration, no-storage, wind/diesel. Initially, this technology is targeted specifically for far northern communities with nominal capacities from about 200 kW to several MW, but it will be applicable to other climates as well.

Apart from its current focus on Hydro-Quebec's HPNSWD technology, the AWTS has a significant capability that could be used for other wind/diesel testing: two diesel gensets with overrunning clutches on the diesel engines, load bank, synchronous condensers, five wind turbines from 35 kW to 80 kW (all delivering AC power), and data acquisition and control. It also offers a unique combination of a harsh winter climate and a marine environment.

NREL's Hybrid Power Test Facility will focus on testing power systems packaged by manufacturers. All these systems will likely include energy storage and will target capacities less than 100 kW. The NREL facility is also unique because of the spectrum of renewable energy sources available—both AC and DC wind turbines and a PV array. In addition, provision will be made for simulating both wind (AC and DC) and PV power.

The USDA facility will be targeted to evaluate wind/diesel power-system technology, both with and without storage. The wind turbines will deliver AC power. The loads will be "real" electrical loads (e.g., induction motors and lighting) rather than simulated loads (load bank). Though the facility capacity nominally will be 100 kW, the research will focus on hardware and systems for a range of sizes, nominally 50 kW to several MW. Also unique to the USDA facility will be the evaluation of vegetable-oil fuels in the diesel gensets.

REFERENCES

1. Reid, R. and Saulnier, B. 1986. "Wind/Diesel Potential for Remote Power Systems: Technico-Economic Aspects." *Proceedings of the Canadian Wind Energy Association 1986 Meeting, Quebec City, October 26–28, 1986.*
2. Reid, R., Saulnier, B., Barry, A.O., Drolet, A., Dubé, B., Lavallée, M. and Martell, L. 1987. "Status of the Wind/Diesel Coupling Activities at Hydro-Québec." *Canadian Wind Energy Association 1987 Annual Meeting, Calgary, Alberta, September 27–30, 1987.*
3. American Wind Energy Association, 1991. "AWEA Standard (AWEA 10.1-1991)." *Wind/Diesel Systems Architecture Guidebook.*
4. Lundsager, P. 1993. *Summary of Recommendations on Hybrid System Model Development.* Consultant Report to NREL, September 20, 1993.
5. Hughes, P. 1992. *Deployment Strategies and Requirements: Controls Strategies and Penetration Levels.* Workshop Report, 6th International Wind/Diesel Workshop, June 16-19, 1992, PEI, Canada.
6. Infield, D. G., Scotney, A., Lundsager, P., Bindner, H., Uhlen, K., Toftevaag, T., and Skarstein, O. 1992. *Wind Diesel Systems—Design Assessment and Future Potential.* Workshop Report, 6th International Wind/Diesel Workshop, June 16-19, 1992, PEI, Canada.

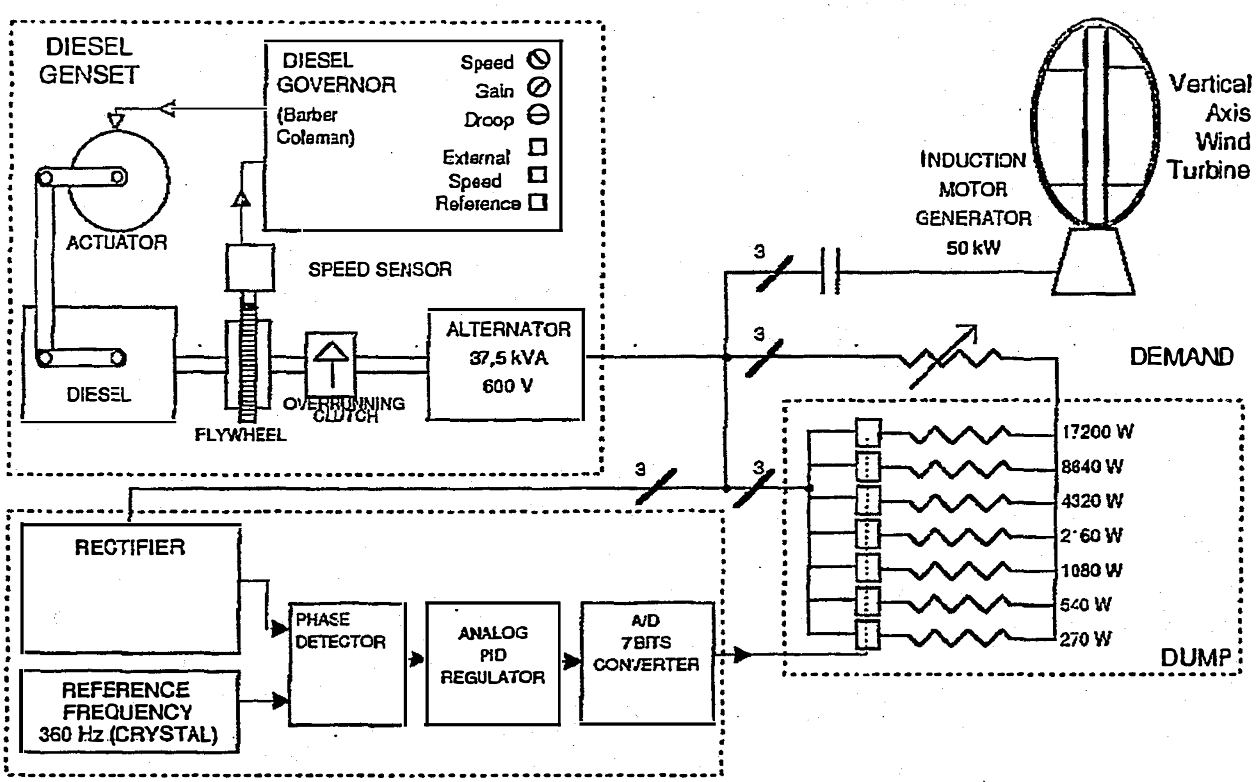


FIG 1. SCHEMATIC OF HYDRO-QUEBEC'S WIND/DIESEL TEST FACILITY.

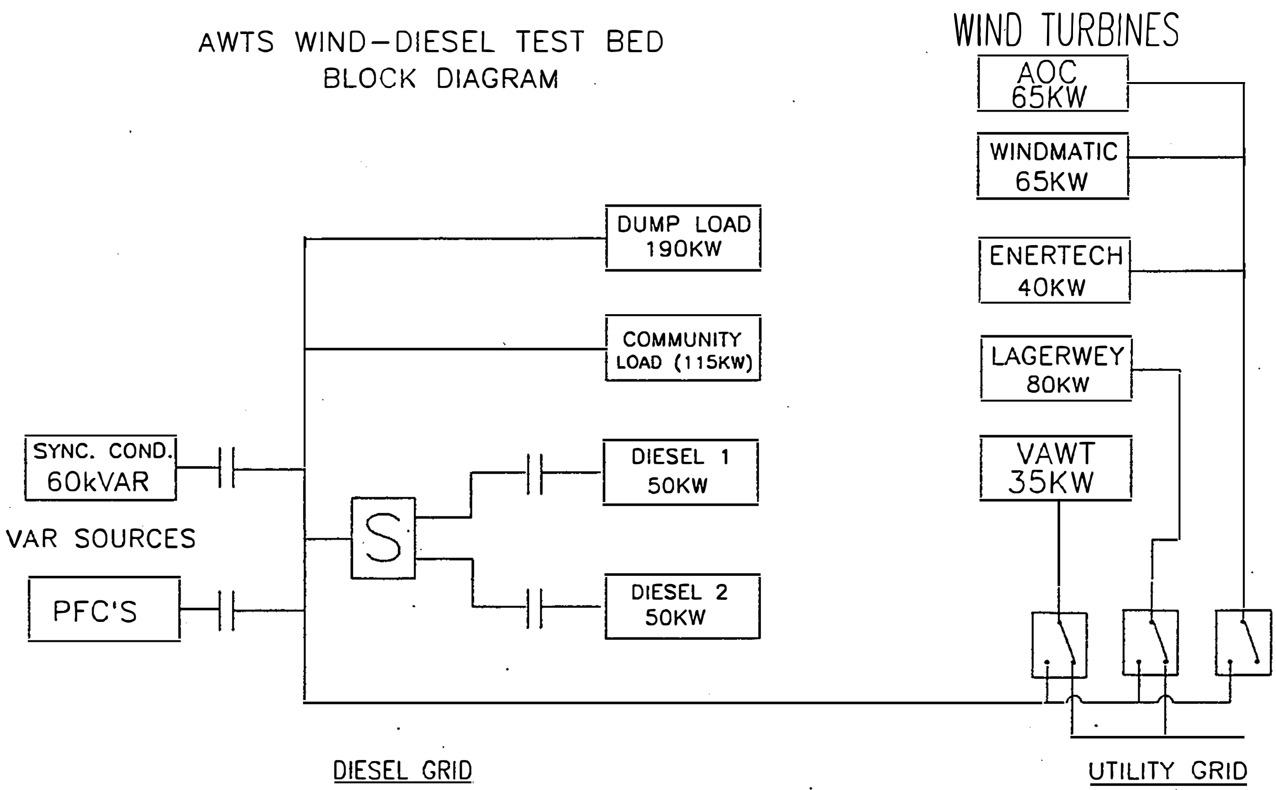


FIG 2. SCHEMATIC OF THE ATLANTIC WIND TEST SITE'S WIND DIESEL DEVELOPMENT AND TEST FACILITY.

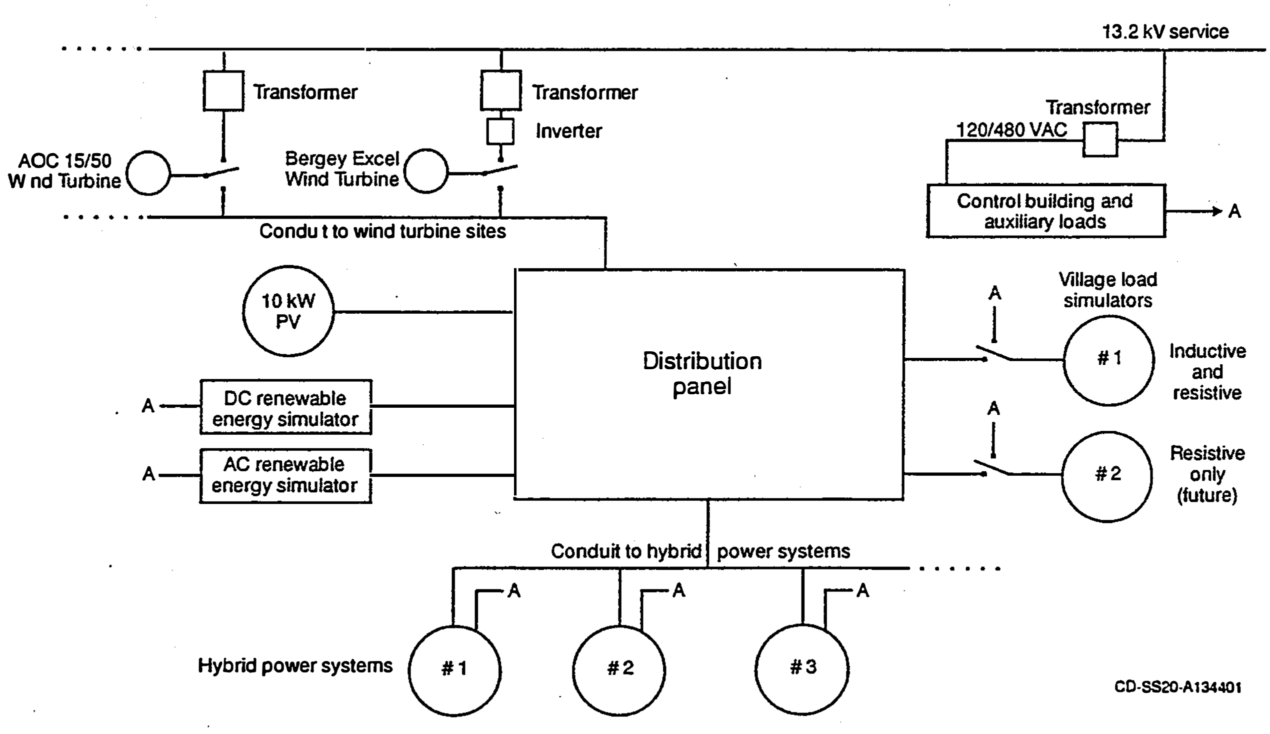
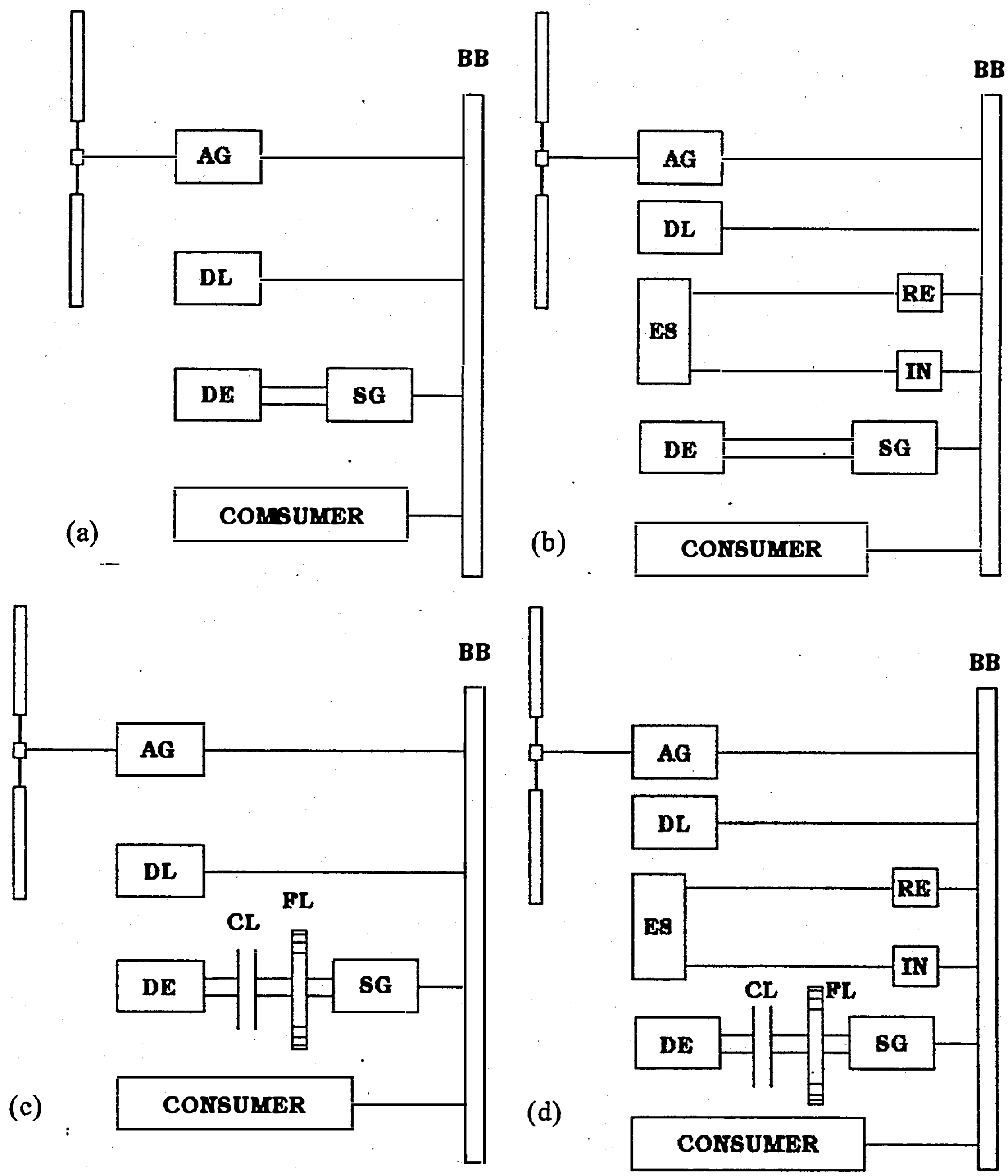


FIG 3. SCHEMATIC OF NREL'S PLANNED HYBRID POWER TEST FACILITY.



AG: Asynchronous generator
DL: Adjustable dump load
DE: Diesel engine
SG: Synchronous generator
CL: Clutch

FL: Flywheel
ES: Energy storage unit
RE: Rectifier
IN: Invertor
BB: Bus bar

FIG 4. (a) SIMPLE WIND/HYBRID SYSTEM WHERE THE ENGINE GENERATOR RUNS CONTINUOUSLY.
(b) SIMPLE WIND/HYBRID SYSTEM WITH ENERGY STORAGE.
(c) COMPLEX WIND/HYBRID SYSTEM WHERE THE ENGINE IS STOPPED AND THE GENERATOR OPERATES AS A SYNCHROUNOUS CONDENSER
(d) COMPLEX WIND/HYBRID SYSTEM WITH ENERGY STORAGE.