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Hybrid Electric Power Generation with Wind and Diesel

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Abstract. *Wind/hybrid operation data were collected using an independent hybrid test grid consisting of three diesel generator sets, AOC 15/50 and Enertech 44/40 wind turbines, two resistive load banks, pre-commercial controls, with a simulated village load. Two configurations were tested, one using a synchronous condenser that included no storage and one with 110 kW of battery storage with a rotary converter. The fuel efficiency increased from 2.63 kWh per liter for diesel only to 4.01 kWh per liter with hybrid system without storage and to 10.09 kWh per liter with battery storage. The potential run time in wind only was greatly increased when the battery storage was added. When wind power was sufficient to curtail the diesel generator sets, control was smooth and stable providing for the entire village load without having to burn fuel.*

Keywords. Wind power, Electric generation, Hybrid, Renewable energy, Wind turbines, Remote power generation, Batteries

Introduction

Many farms and communities exist in remote places where it is unlikely that they will ever be connected to large utility girds. These farms and communities depend on costly diesel fuel for electric power generation and often store several months supply of diesel fuel on site. Electrical costs at these locations often range from 30 to 50 cents per kilowatt-hour (kWh). Reducing the fuel expense by using local, renewable energy sources is the focus of wind/hybrid research and development.

One way to reduce diesel fuel usage is to add wind turbines to the existing diesel mini-grid so that diesel generator sets run less and save fuel. Larger wind plants have more potential for fuel savings, but require sophisticated electronic grid controls. Constructing a hybrid system that works, developing the necessary controls, and evaluating the performance were primary objectives of this study.

Test Configuration

Two wind/hybrid test configurations have been tested over the last four years at the USDA, Agricultural Research Service, Wind/Hybrid Research Laboratory (WHRL) located in Bushland, TX. The configurations were similar except of the addition of short-term energy storage included in the present configuration. The test configuration contained two wind turbines, three diesel engines, and two load banks, one for simulating the village load and one for consuming the excess power. Any electric grid must always operate in balance with all power generated being consumed.

The first test configuration consisted of an AOC 15/50 and an Enertech 44/40 wind turbine[1], three Caterpillar 3304, 40 kW diesel generators, a synchronous condenser, a village load simulator consisting of three motor loads and a 100 kW resistive heater load, and a 200 kW resistive heater load for system controlled dumping of excess wind power. This configuration is shown in Figure 1. The second configuration tested consisted of the wind turbines, diesel generators, village loads and balancer load as well as a battery storage rated at 100 kW for 10 minutes and a rotary converter for converting the DC power to AC to match the remainder of the hybrid grid. This configuration is shown in Figure 2.

A representative village load profile was selected and time-compressed so that 24 hours of profile would run on the system in just 12 hours. The average village load was 35.4 kW, with minimum and maximum loads being 15 kW and 65 kW respectively. The average installed wind power penetration was 250% (rated wind power/average village load). The village load was configured to include resistance heaters and water pump motors. The system controller maintained the appropriate frequency by dispatching sufficient diesel capacity and/or increasing the dump load to match the available wind power.

The test plan also included power quality and reliability goals. The average frequency was to be 60 Hz (+/-0.2 Hz) and the average voltage was to be 480 VAC (+/-20 Volts). The frequency range was to be held between 55 Hz and 65 Hz and the voltage between 440 VAC and 520 VAC. The power reliability goal was less than 5 outages per 1,000 hours of operation. Phrased another way, the average time between outages was to be greater than 200 hours.

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[1]The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

The data were collected within the experimental control system with one data line each 10 minute interval. Fuel flow and power measurements were averaged over 10 minutes, while average, minimum and maximums were collected on voltage and frequency. The data were processed using Microsoft Access and Excel.

Results

The system was operated in the configuration without storage for about nine months and has been operated for about six months in the configuration with storage. During both testing periods, wind turbine controller problems have plagued the testing program. In both cases, severe lightning damaged the AOC wind turbine controller causing significant delays. The current limiting starting system on the Enertech also contributed to reduced testing time.

Configuration Without Storage

Data was collected for 952 hours in the test configuration without storage, described as an AC bus, high penetration, no storage, with total diesel plant shut down allowed if the wind power is sufficient. The 952 hours of data contained 432 hours of diesel-only operation, 492 hours of wind-diesel operation, and 17 hours of wind-only operation. Minor adjustments were made during the test period to attain better reliability and increased performance.

The winds at an anemometer height of 10 meters above the ground averaged 6 m/s and the highest 10 minute averaged record was 18.6 m/s. More than 150 hours of data were collected at winds above 10 m/s.

During the 431 hours of diesel-only operation, the average fuel efficiency was 2.63 kWh delivered to the village per liter of fuel. This jumped to 4.01 kWh per liter of fuel for a 52% increase in fuel efficiency for wind-diesel operation. For the entire 952 hours of operation, the system averaged 3.20 kWh per liter of fuel for about a 22% fuel saving. The average penetration of wind energy of the village load was 25.37% and varied from 50.27% when operating in wind-diesel to 100% in wind-only, and 0.00% in diesel-only. Over the entire run, 76.16% of the village energy came from the diesel engines. About 26% of the total energy was overhead and consisted of dump load and diesel cooling fan motors, transformers, diesel water jacket heaters, and control system requirements.

Table 1 summarizes the hybrid system's operation without storage and energy flows. Data are presented for the entire run, diesel-only, wind-diesel, and wind-only operation. Wind-only operation is considered a special case of wind-diesel operation and is included in the data for wind-diesel operation, as well as shown separately. The number of hours may not agree with the total due to the exclusion of data during operational transitions.

Configuration With Storage

Data for this configuration has been collected for only 192 hours due to various problems with the wind turbine controllers caused mainly by lightning damage to the electronics. The 192 hours contains 87 hours of diesel-only operation, 53 hours of wind-diesel operation and 51 hours of wind-only operation. No adjustments have been made to this initial set-up to improve operation time or performance.

During the 83 hours of diesel-only operation, the average fuel efficiency was 2.64 kWh per liter of fuel. The fuel efficiency increased to 10.09 kWh per liter of fuel when the system was operated in wind-diesel for a 287% increase in fuel efficiency. This large increase in fuel efficiency is partially due to the 13% penetration by the batteries toward the village load. The overall average penetration of wind energy was 31.11% and varied from 36.70% for wind-diesel to 78.78% in wind-only. In both cases, the batteries carried a significant portion of the load when the wind-turbines were operating. The batteries contributed 13.23% in wind-diesel and 21.22% in wind-only operation.

Table 2 summarizes the hybrid system operation with storage and corresponding energy flows. Information has been added to show the contribution from the batteries. The data are summarized similarly to data presented in Table 1 for operation without storage.

The addition of batteries to the wind/hybrid system increased the overall fuel efficiency from 3.20 kWh per liter of fuel to 6.18 kWh per liter of fuel; thus producing almost twice as much energy per liter of fuel. The use of batteries also increased the portion of time that the system operated in wind-only. Without storage, the system operated about 2% of the time in wind-only and with batteries it increased to 26% of the time.

Power Quality and Reliability

Both systems met the goals for average voltage (480 VAC, +/- 20 Volts) and frequency (60 Hz +/-0.2 Hz) power quality. Out of the 5960 extreme, instantaneous data points during operation without storage, the system had 32 data points below 440 volts (but none over 520 volts), 1 data point under 55 Hz, and 2 data points over 65 Hz. While these points were outside the range desired, they were of short duration and their impact appeared to have been minimal.

A total of 17 outages were recorded during the 952 hours of testing, which is an average of 56 hours between outages. The causes of power outages were: 3 outages for blown dump load fuses, 3 outages for diesel #1 failing to start, 2 outages for not having enough capacity online to start the synchronous condenser and turbines, 3 outages for low frequency errors, one outage for a low voltage error, one outages for a utility power blackout, and 4 outages of undetermined origin. At the beginning of the testing period the average time between power outages was 25 hours. Over the course of testing, this figure was improved to an average time between power outages of 177 hours. Some more improvement is necessary to operate 200 hours between blackouts.

The rotary converter that was used with the batteries does not respond as quickly as the synchronous condenser and allows the system to stop due to an outage. This rotary converter is used both to charge the batteries and to draw power from the batteries; therefore, it must sometimes change the flow of electricity within a very short time period. Additional adjustments to this controller will be made to eliminate the rotary converter outages.

The microprocessor controls of each diesel, and the hybrid system controller proved quite reliable. However, the operator interface and data logging was done by an industrial computer (CPM) running Windows. When this computer had difficulties, the operator was unable to log data, or even identify system warnings or alarms other than engine faults. If the CPM does not work, for whatever reason, operational fault diagnosis may be extremely difficult.

Conclusion

While testing, the hybrid system performed well; however, it did not quite meet all the specified performance and reliability goals. The average frequency and voltage were within specified limits, though some very occasional voltage and frequency excursions were observed. In general the power quality was good. The fuel efficiency increased from 2.63 kWh per liter for diesel only to 4.01 kWh per liter with hybrid system without storage and to 10.09 kWh per liter with battery storage. The potential run time in wind only was greatly increased when the battery storage was added. The wind energy penetration varied from 0% to 100%, depending upon wind conditions and the village load. When wind power was sufficient to curtail the diesel generator sets, control was smooth and stable providing for the entire village load without having to burn fuel. Some systematic improvement in the control logic will be necessary to increase the average time between power outages, especially with the rotary converter controller.

Acknowledgements

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Table 1: Energy Summary for Configuration Without Storage

Entire Run	952	hours			
Total Production	52242	KWh	Consumption	52242	kWh
Diesel	27926	kWh	Village	33695	kWh
Wind	24316	kWh	Dump	16584	kWh
Fuel Efficiency	3.20	kWh/liter	Wind Dump	15742	kWh
Wind Penetration	25.37	Energy %	Diesel Dump	842	kWh
Diesel Penetration	76.16	Energy %	Overhead	1963	kWh
Diesel-Only	432	hours			
Total Production	15651	kWh	Consumption	15651	kWh
Diesel	15651	kWh	Village	15470	kWh
Wind	0	kWh	Dump	0	kWh
Fuel Efficiency	2.63	kWh/liter	Wind Dump	0	kWh
Wind Penetration	0.00	Energy %	Diesel Dump	0	kWh
Diesel Penetration	100.00	Energy %	Overhead	182	kWh
Wind-Diesel	492	hours			
Total Production	31278	kWh	Consumption	31278	kWh
Diesel	9827	kWh	Village	15043	kWh
Wind	21452	kWh	Dump	14302	kWh
Fuel Efficiency	4.01	kWh/liter	Wind Dump	13863	kWh
Wind Penetration	50.27	Energy %	Diesel Dump	439	kWh
Diesel Penetration	55.86	Energy %	Overhead	1818	kWh
Wind-Only	17	hours			
Total Production	1485	kWh	Consumption	1485	kWh
Diesel	0	kWh	Village	348	kWh
Wind	1485	kWh	Dump	992	kWh
Fuel Efficiency	Very Large	kWh/liter	Wind Dump	992	kWh
Wind Penetration	100.00	Energy %	Diesel Dump	0	kWh
Diesel Penetration	0.00	Energy %	Overhead	145	kWh

Table 2: Energy Summary for Configuration With Storage

Entire Run	191.7	Hours			
Total Production	9,082	kWh	Consumption	9,082	kWh
Diesel	4,068	kWh	Village	5,357	kWh
Wind	4,325	kWh	Dump	2,177	kWh
Battery	689	kWh	Wind Dump	2,068	kWh
Fuel Efficiency	6.18	kWh/liter	Diesel Dump	109	kWh
Wind Penetration	31.11	Energy %	Overhead	1,548	kWh
Diesel Penetration	57.34	Energy %			
Battery Penetration	9.98	Energy %			

Diesel-Only	87.3	Hours			
Total Production	2,745	kWh	Consumption	2,745	kWh
Diesel	2,743	kWh	Village	2,551	kWh
Wind	-	kWh	Dump	88	kWh
Battery	2	kWh	Wind Dump	-	kWh
Fuel Efficiency	2.64	kWh/liter	Diesel Dump	88	kWh
Wind Penetration	-	Energy %	Overhead	106	kWh
Diesel Penetration	99.92	Energy %			
Battery Penetration	0.08	Energy %			

Wind-Diesel	53.5	Hours			
Total Production	3,401	kWh	Consumption	3,401	kWh
Diesel	1,325	kWh	Village	1,913	kWh
Wind	1,726	kWh	Dump	754	kWh
Battery	350	kWh	Wind Dump	716	kWh
Fuel Efficiency	10.09	kWh/liter	Diesel Dump	38	kWh
Wind Penetration	36.70	Energy %	Overhead	733	kWh
Diesel Penetration	48.64	Energy %			
Battery Penetration	13.23	Energy %			

Wind-Only	50.8	Hours			
Total Production	2,941	kWh	Consumption	2,941	kWh
Diesel	-	kWh	Village	893	kWh
Wind	2,600	kWh	Dump	1,335	kWh
Battery	341	kWh	Wind Dump	1,335	kWh
Fuel Efficiency	Very Large	kWh/liter	Diesel Dump	-	kWh
Wind Penetration	78.78	Energy %	Overhead	713	kWh
Diesel Penetration	-	Energy %			
Battery Penetration	21.22	Energy %			

Hybrid System Without Storage

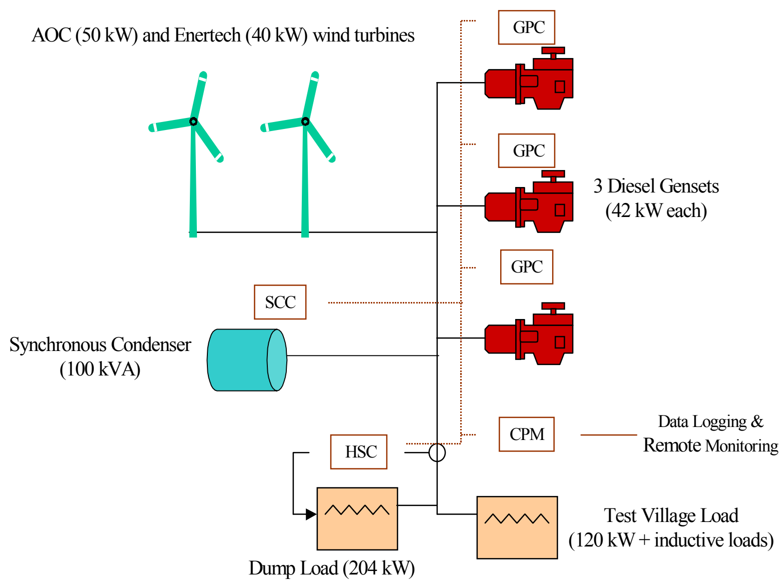

Figure 1 Line drawing of hybrid system without storage.

Hybrid System With Storage

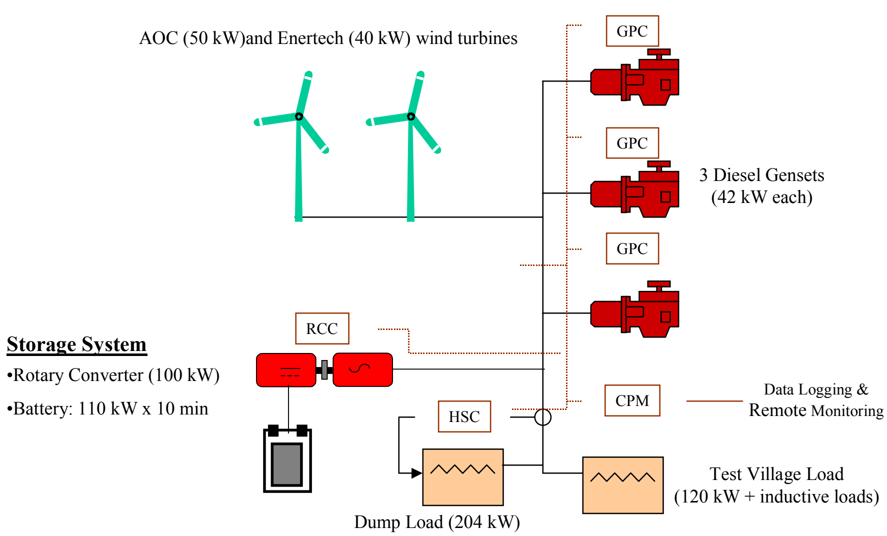

Figure 2 Line drawing of hybrid system with battery storage.

Figure 3 Photographs of diesel generators, wind turbines, and resistive loads.