OPERATIONAL EXPERIENCE WITH WIND/HYBRID CONTROLS[1]

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Abstract

A wind/hybrid generating system consisting of a single diesel generator, a 50 kW wind turbine, a resistive load bank, custom controls and a simulated village load was constructed by the USDA Agricultural Research Service. The configuration was high penetration, no storage, without allowing diesel shut down. Control strategies for three operational modes are discussed, along with the decisions that must be made to make the transitions between modes. Crossing these transitions creates some unique situations that require special decision tools and programing. Some of our experiences in overcoming these programing issues are presented. Software decision timing must match the sampling time of control sensors because you can not force decisions faster than sensors measure changes due to those decisions.

Introduction

Wind turbines and diesel generators have operated independently to provide electric power for a number of years. However, there is a desire to combine them into a single generating system. Controls for such a system had to be constructed. The experience gained from the USDA/DOE Wind/Hybrid Research Program may be instructive to others interested in constructing similar hybrid systems.

Wind penetration for hybrid systems is defined as the rated wind power divided by the rated consumer load. Low penetration systems (less than 70%) and offer only small economic benefits because the diesel engine continues to run. Rarely do wind systems and consumer loads operate at rated levels, but normally run between 40 and 60%. Wind power reduces diesel loading, but the efficiency of the diesel plant is usually also reduced. The net effect is that the diesel fuel consumed may only drop on the order 10%, and the economic benefit of adding wind power is low. With high penetration systems (greater than 100%), diesels may be shut down completely, saving all the fuel usually consumed during high wind periods. The possible economic benefit of high penetration systems is therefore much higher than for low penetration systems. The central issue is how to make high penetrating controls robust, reliable, and marketable. This is the objective for the wind/diesel hybrid research conducted by the USDA-Agricultural Research Service.

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[1] Contribution from USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX 79012 in cooperation with the Department of Energy, National Renewable Energy Laboratory, Golden, CO, and the Alternative Energy Institute, West Texas A&M University, Canyon, TX.

Another issue to be considered is the use of energy storage. The benefit of storage is the ability to save wind power for use later when it is needed, instead of burning diesel fuel. Unfortunately, large bulk electrical energy storage systems are very costly, so long term energy storage is usually not considered further. Short term energy storage could be much cheaper, yet still yield the benefits of reduced wear and tear on diesel engines and simplified controls. However, the economics of even short term storage may not be sufficient to off-set the cost. After all, the choice is between a large up-front investment in energy storage equipment, versus slightly more diesel fuel consumption and engine maintenance. While there has been no definitive answer to the storage question and this research program intends to look at this issue in the near future, storage was omitted from early test plans to simplify matters. Our initial test configuration can be defined as high penetration with no storage.

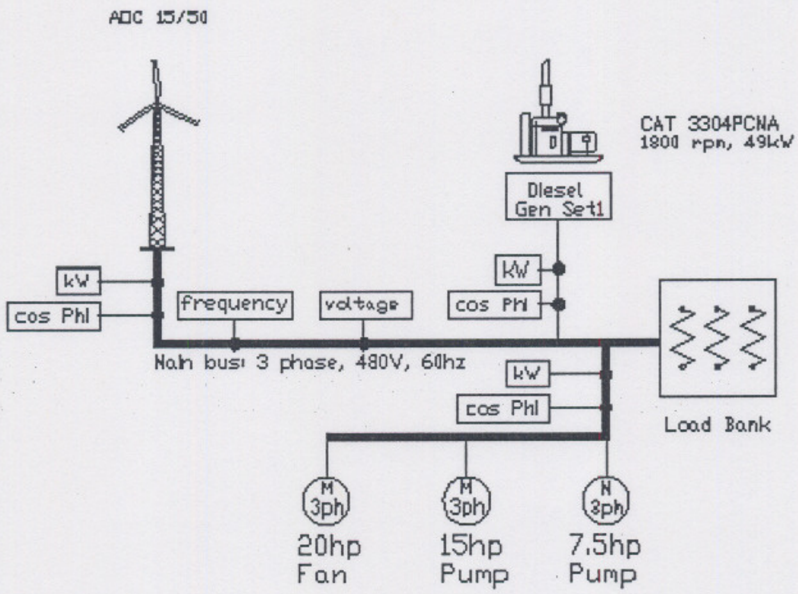

FIGURE 1: TEST CONFIGURATION USED FOR 1998 WIND/HYBRID GENERATION EXPERIMENTS.

Configuration

The test configuration consisted of an AOC 15/50[2] wind turbine, a Catepillar 3304PCNA, 49 kW diesel generator, three motor loads, and a dual-duty load bank for village load simulation and controlled dumping of excess wind power. Running a 40 kW constant village load, installed wind penetration is 125% (rated wind power/village load). Instantaneous penetration can be as high as 200% because the turbine can reach over 80

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[2] 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.

kW for short periods. The diesel runs continuously and only shuts down for system errors or operator commands.

Operational Modes

The USDA wind/diesel hybrid system has three operational modes:
1. Diesel only - diesel meets the entire load and wind is not sufficient to start the wind turbines.
2. Wind/Diesel - load is shared between diesels and wind turbines.
3. Wind only - wind turbines meet the entire load and all diesels are curtailed.

Diesel Only
Diesel only operation is no different than normal engine generation. Synchronizing and load sharing between diesels, dispatch of diesels for load coverage and necessary exercise, and service lock-outs remain as in normal operation. Diesel regulation was "droop" -- the engine governor would respond to load changes by increasing fuel flow, but allowing the frequency to drop slightly. The no-load setting for the governor was 60.4 Hz and this drooped to about 58.6 Hz at full load. Such droop diesel regulation is common on small diesel generators. On large units, isochronous electronic controls which effectively eliminate frequency variation are normally used.

Wind/Diesel
Wind/diesel operation mode occurs when wind turbines shares the load with the diesel plant. Power balance control must be shared between the diesel governor and the system control under droop operation. When large amounts of wind power are available, the diesel is throttled back to its minimum load. If this did not balance power, a progressive deferrable balancer load (usually called a dump load) is switched on, to bring power demand up to meet the available supply. Two items control power balance and frequency: the diesel governor brought the frequency up, while the balancer load brought it down. (It is important to note that part of the balancer load may be a deferrable customer use such as building and water heating.) In the wind diesel mode, wind power should become the preferred and accepted power supply, when available, since no fuel costs are incurred. Diesel power should be used to fill the gap between consumer load power demand and wind power supply.

Wind Only
Wind Only operation occurred when the wind power was adequate to comfortably supply the entire consumer load -- and the entire diesel plant was shutdown. Diesels were all shut off and the synchronous condenser provided the excitation necessary to keep the induction wind turbines running and producing power. Synchronous condensers (actually synchronous generators without a prime mover, on-line, spinning) are often used to supply reactive power to the wind turbines and provide some inertia to smooth quick changes in frequency and balance. The system control maintained the frequency by changing the balancer load level to consume any excess generation and looked for any intolerable frequency droop. A power shortfall was met by either starting a diesel quickly or, drawing power from storage unit (if installed). A frequency of 60+/- 0.5 Hz is acceptable under normal conditions.

Transitions Between Modes

The hybrid system will operate easily once it is balanced within a given mode. However, when the wind speed changes and the wind turbine power shifts, a change in modes is required. It is the mode transitions that exercise the control system and make the hybrid control system unique.

Diesel to Wind/Diesel Transition

To switch to wind/diesel from normal diesel only operation, available wind turbines are enabled and the balancer load is enabled. A single digital control signal from the system controller enables or disables individual turbines through their dedicated controller. Our wind turbines have two types of dedicated controllers: electronic soft-start and wind soft-start.

Most wind turbines made in the early 1980s had hard-starters (across the line connection). When wind was sufficient, the main contactor connected the wind generator directly to the utility line, the in-rush current was 6 to 10 times the generator's normal full load current for a few seconds and the rotor motored up to speed. When operating speed was attained, the wind would push the generator to slip positive (ahead of the utility up to about 3%) and commence wind power generation. The in-rush and connection transient of such a starter would sag the utility line's voltage in the local area, demand a huge amount of power for a short time, and generally anger the utility. For most wind diesel hybrid systems, this type of wind turbine starter is unacceptable because the demand on the diesel plant is too high, causing the entire system to crash. The alternative is a soft-start turbine.

When enough wind is detected for wind power generation, an electric soft-starter gradually motors the turbine up to speed, drawing power from the grid over about 30 seconds to reduce the in-rush transient. If the wind plant is comprised of multiple electric soft-started turbines, they should never all be enabled at the same moment, in order to prevent the possibility of them demanding transient starting power at the same time. Still, excess diesel generation capacity is necessary to start wind turbines in this way.

When enabled in sufficient wind, a wind soft-started turbine releases the brake and allows the wind to gradually blow the rotor up to connection speed. In some wind conditions there may be a voltage transient upon connection. These are not usually large enough to perturb the system as a whole. Since there is negligible power demand to start a turbine this way, these type of starters are much preferred for use in wind/diesel systems. With any turbine starting method, each turbine enable signal should be staggered by a minute or two to reduce the opportunity for connection transients to occur at the same moment.

Wind/Diesel back to Diesel Transition

This transition happens in two conditions with low wind stoppage having little or no effect and manual curtailment under load requiring care not to crash the system. Operator curtailment of wind generation capacity is critical with this transition. Because the wind turbines may be carrying a large portion of the load in good winds, turbines should be curtailed slowly or in staggered fashion while diesel capacity is increased to accept the additional load. In low wind conditions; however, each turbine shuts down by itself when it is generating little or no power and usually won't have an adverse affect on the system.

Wind/Diesel to W/D Fault Transition
System errors of frequency or voltage in the wind/diesel mode are likely to be due to problems with turbines, balancer load, or their control. By curtailing operation of wind turbines and balancer load, these errors may be handled without shutting down the entire system.

Each turbine has its own controller that handles all turbine errors, feeder phase voltage sags, or grid blackout in order to operate the turbine safely. Overload protection and manual disconnects are incorporated into each turbine control box. Electrical connection to the diesel grid is exactly the same as for connection to a utility line. When disabled, each turbine executes its own shut down procedure and disconnects from the hybrid grid.

A balancer load error usually means that the cooling fan has failed and that the resistive elements are in danger of burning out. To protect equipment, the system control must terminate use of the balancer load. If this occurs, control over wind power will be lost, and wind generation must be curtailed and the system returned to diesel only operation.

W/D Fault to Diesel Transition
Once the balancer load and turbines have been successfully shut down, operation continues in the Diesel Only mode with Wind/Diesel operation locked-out until problems are fixed and the operator removes the lock-out.

Balancer Load

The steps that control the balance load are actuated through several rules. The primary rule is to maintain the operator's minimum power setting for the diesel currently on-line. If a diesel is not needed, it will be curtailed. Otherwise, load will be added to bring each diesel up to a designated minimum load. This is done because most engines do not last a long time if run lightly loaded for extended periods. Wear seems to accelerate under these conditions, and most diesel warrantees are voided by such treatment.

Next come the droop mode operational rules. The frequency error (FE) is calculated by subtracting the current frequency measurement from the desired pre-set frequency. The change in frequency (FC) is calculated by subtracting the current frequency measurement from the last frequency measurement. Both the FE and FC may be multiplied by input gains, which have been set in the controller, before being used as inputs to a fuzzy logic table such as the one shown in Table 1.

The field selected from this table is then multiplied by a pre-set output gain and combined with the minimum diesel load level rule output to determine the appropriate balancer load level for the next time interval. This time interval between control commands must be at least as long as the time required for a new frequency sample.

If the frequency transducer fails, the system control may be forced to shut down the entire system. Therefore, frequency transducers become critical components for control of the entire system. In addition, electronic turbine soft-starters can distort the AC wave form enough to destroy frequency measurements derived from counting zero voltage crosses during the sampling period. Such transients that distort frequency measurements must be avoided or accommodated in the controller.

TABLE 1: FUZZY LOGIC DECISION TABLE

FE\FC	+0.8	+0.4	+0.2	+0.1	0	-0.1	-0.2	-0.4	-0.8
+4	-96	-48	-24	-12	-6	-6	-3	-1	-3
+2	-48	-24	-12	-6	-6	-3	-1	-3	1
+1	-24	-12	-6	-3	-3	-1	-1	1	3
+0.5	-12	-6	-3	-1	-1	-0.5	1	3	6
0	-6	-6	-3	-0.2	0	0.2	3	6	6
-0.5	-6	-3	-1	0.5	1	1	3	6	12
-1	-3	-1	1	1	3	3	6	12	24
-2	-1	3	1	3	6	6	12	24	48
-4	3	1	3	6	6	12	24	48	96

Operational Experience

Conflicts between the balancer load control and the diesel governor result in two undesirable tendencies: back-driving the diesel below minimum load, or dumping diesel generated power. To avoid these, the diesel governor must be adjusted so that the diesel becomes unloaded at about the same frequency that the dump load starts actuating. With a high, gusty wind and the system control half a second behind reality (400 ms per control loop execution due to frequency sampling rate), one can always expect short bursts of diesel back-driving and/or dumping of diesel power. With proper adjustment, conflicts and dumped diesel energy can be minimized.

The system sustained damage to the wind turbine controller as a result of our first error shut-down. We had naively thought that telling the diesel to shut off and de-energizing all the contactors in the wind turbine system was appropriate. When disconnected, the turbine went through an emergency stop, as it would with a blackout when connected to the utility grid. However, the turbine's generator still had an excitation field trying to collapse -- with nowhere to go. The result was a very high voltage spike on the turbine side which blew a surge suppressor, a main fuse, and a few components and traces off the controller board's power supply section. Repairs and error handling changes were required before further operation.

Error handling was changed to leave the load connected and increase the load bank to maximum; then, tell the diesel and turbine to shut off, by way of their respective controllers. This eliminated problems caused by an error shut-down.

We had no trouble starting the AOC 15/50; however, when we tried to connect our Enertech 44/40 turbine, which had an electronic soft-starter, the electronic soft-starter distorted the AC wave form enough to destroy frequency measurements derived from counting zero voltage crosses. It appeared that the tail of each half cycle was clipped, hovering near zero and causing the frequency transducer to see high phantom frequency -- which then caused a high frequency error shut-down of the whole system.

We identified a number of critical control parameters that needed set points. These included: minimum diesel power, diesel governor setting, frequency transducer sampling and system decision rate, the fuzzy logic control map, input gains for frequency error (FE) and frequency change (FC), and the fuzzy logic map output gain. All the gains could be eliminated from the control program and the fuzzy logic map manipulated directly, but it becomes harder to iterate toward optimal values. To pick the right settings in an academic, deterministic style one would need to do quite a bit of dynamic modeling with time constants, inertias, and lots of other information that almost no manufacturer can quote, and which require a large effort to determine experimentally. Or, you can build the system, find a quick sampling frequency transducer, guess at the gains, and calculate and iterate until the system is optimized and running very well. We followed the latter method.

It does help to know about effects and inter-relationships. In larger diesels and wind turbines, the inertias become larger and systems react more slowly to changes in load or wind power. Likewise, smaller systems react more quickly and require faster controls. With our 49 kW diesel and 50 kW turbine system, a 400 ms reaction time worked well in mild conditions, but was too slow to handle harsh conditions. In harsh conditions, with our rather droopy diesel, frequency swings from 59 to 61 Hz did occur. As previously mentioned, short term back driving of the diesel and dumping of diesel power is another undesirable result. Computer control can be done much faster without trouble, but a faster, more robust frequency transducer is required.

While operating over 100% penetration, the frequency does tend to oscillate with a period of 2 to 3 seconds and similar trends have been observed in other hybrid systems within the wind/diesel literature. By observation, each parameter seemed to have an optimal value. With each gain set too high or low, frequency swings appear to get worse. Flatter diesel governor droop would substantially reduce frequency swings. And the control time step and decision rate probably have optimal values as well, given the system size, inertia, and reaction time.

Future Testing

The initial configuration did not allow Wind Only operation or include energy storage. We are currently in the process of adding two additional diesel generators, a synchronous condenser, and commercial controls to allow research into these issues. We can report that the system has operated in the wind only mode, but not enough data has been taken for any conclusions to be drawn. Energy storage is included in next year's test plan.

Conclusion

The control algorithm described above has operated for over 1000 hours with penetration as high as 250%. Details and performance data from these initial tests was presented in a paper by Clark and Eggleston (1999). It has performed well, though not perfectly. Problems have been identified concerning wind turbine soft starters, frequency transducers, and the time step for control decisions. Most of these have been driven by system hardware, rather than software issues. While somewhat tedious, the testing and selection of optimal control parameters is straight forward. Without hardware limitations like a slow, vulnerable frequency transducer, control optimization would have progressed much more quickly.

References

Clark, R. Nolan and Eric D. Eggleston. 1999. Wind/hybrid operation with biodiesel. Proc of 1999 ASME Wind Energy Symposium, AIAA-ASME. pp 287-292.

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