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POWER FLOW MANAGEMENT IN A HIGH PENETRATION WIND-DIESEL HYBRID POWER SYSTEM WITH SHORT-TERM ENERGY STORAGE

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INTRODUCTION

In the last several years, interest in medium to large scale (100 kW to multi-MW) wind-diesel hybrid power systems for rural electrification has grown enormously among energy officials and utility planners in the developing countries, multilateral lending institutions, and utilities serving the far northern areas of the developed countries. There are many indications that there is a large potential market for such systems, and though there are an increasing number of demonstration projects, a true market for such systems has yet to emerge. Consequently, an industry capable of serving this market is still only in its infancy. Only a small fraction of researchers and engineers working in the wind power industry, which is relatively small itself, are involved in hybrid systems for off-grid applications. There is therefore relatively little information available on the technical issues involved in implementing a wind-diesel power system.

It is tempting to view the addition of wind turbines to a diesel mini-grid as a straightforward task, only slightly more complicated than a conventional grid-connected installation, requiring only a few ancillary components at a relatively modest cost. While this is true for low penetration wind-diesel systems, where the wind turbine output averages no more than about 15% of the load, high penetration systems, in which the average wind power generated can approach or even exceed the average load, require much more sophisticated controllers and more extensive components in addition to the wind turbines. This additional cost and complexity can often be justified by the much greater fuel savings (and associated environmental benefits) and reduced diesel operating time made possible by high wind penetration.

This paper is intended as an introduction to some of the control challenges faced by developers of high penetration wind-diesel systems, with a focus on the management of power flows in order to achieve precise regulation of frequency and voltage in the face of rapidly varying wind power input and load conditions. The control algorithms presented herein are being implemented in the National Renewable Energy Laboratory (NREL) high penetration wind-diesel system controller that will be installed in the village of Wales, Alaska, in early 2000.

BACKGROUND

Since 1995, the National Wind Technology Center (NWTC) at NREL has been researching wind-diesel hybrid power systems. Areas of study have included optimal diesel dispatch strategies, the value of energy storage, village mini-grid optimization, power converter efficiency, system stability, and long-term performance and economic modeling. In 1997, the Hybrid Power Test Bed was constructed at the NWTC to facilitate the development and testing of both experimental and commercial hybrid power systems.

One of the ways NREL supports the development and growth of the renewables-based hybrid power systems industry is to provide technical assistance to pilot and demonstration projects, both domestically and internationally. Since 1995, NREL has been engaged in a collaborative project with the Alaska state energy office and Kotzebue Electric Association, a rural Alaskan electric cooperative, to design, test, install, and monitor a high penetration wind-diesel hybrid power system in Wales, Alaska, a small village on the northwest coast on the Bering Strait. NREL's role in this project has been the following:

- Identify a hybrid system architecture well suited to implementation in small northern villages
- Design and build the non-wind turbine hardware components of the system (system controller, secondary load controllers, energy storage subsystem)
- Develop the control software necessary to operate the system stably and reliably
- Fully test and debug the control system at its test facility in Boulder, Colorado
- Provide training in system operation and maintenance.

The control system, the secondary load controllers, and the energy storage subsystem have all been built and installed at the Hybrid Power Test Bed, where the control software is currently undergoing test and refinement. Installation of the system in the village of Wales is scheduled to begin in July 1999.

SYSTEM DESIGN OBJECTIVES

Because of NREL's substantial technical involvement in the project and the availability of its hybrid power test facility, this project represented an opportunity to develop and test a system to meet design and performance objectives beyond what could be met by then-available commercial hybrid power systems. Some of the specific objectives that guided the development of the system are the following:

1. One requirement of the system architecture was that it be designed to "wrap around" an existing village power plant. Unlike many remote regions of developing countries, nearly 100% of Alaska's rural villages are already electrified. These village power systems represent a considerable investment in diesel generation equipment. It is important in these cases to use as much of the existing diesel genset and controls equipment as possible.

2. Second, the system should have sufficient penetration to achieve at least a 50% reduction in the diesel fuel consumed for electric power generation.

3. To maximize the potential fuel savings and to reduce diesel maintenance expenses, the system should allow the diesel generators to be shut off as much of the time as possible. Prior analysis at NREL had suggested that this objective required that the system include a small amount of high power density energy storage.

4. To further maximize the return on investment, the system needs to ensure that 100% of the wind turbines' energy output serves a productive load. In other words, wind power in excess of what was needed to meet the primary village electric demand must be diverted to another application having economic value. In Wales, the only other significant energy demand is for space heating. Because the major heat loads exist at several distributed points in the village, a distributed secondary load arrangement was required.

The architecture chosen to meet these objectives is shown, in simplified form, in Figure 1. The existing diesel power station consists of three 480 VAC, three phase generator sets with ratings of 75, 142, and 148 kW. The retrofit package consists of two AOC 65 kW wind turbines, an AC-DC rotary converter, a 240 VDC 130 Ah nickel-cadmium (Ni-Cd) battery, and several secondary load controllers to control power to electric boilers located at several points in the village. These secondary loads will be used to displace heating fuel that would otherwise be burned in existing boilers. Figure 1 shows only the power components, not the variety of control hardware required to make the system operate. Figure 2 depicts the control architecture of the system. Control signals pass among the various control components either via hardwired analog and discrete control lines, or via high speed serial networks, as shown.

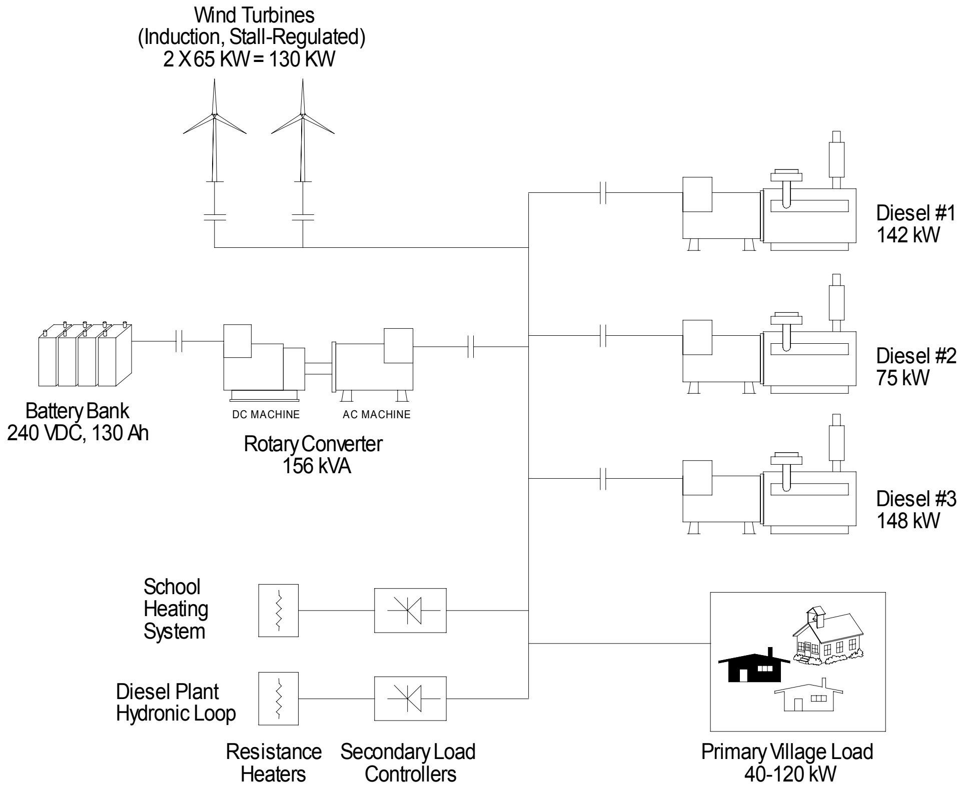

FIGURE 1. WIND-DIESEL SYSTEM ARCHITECTURE FOR WALES, ALASKA

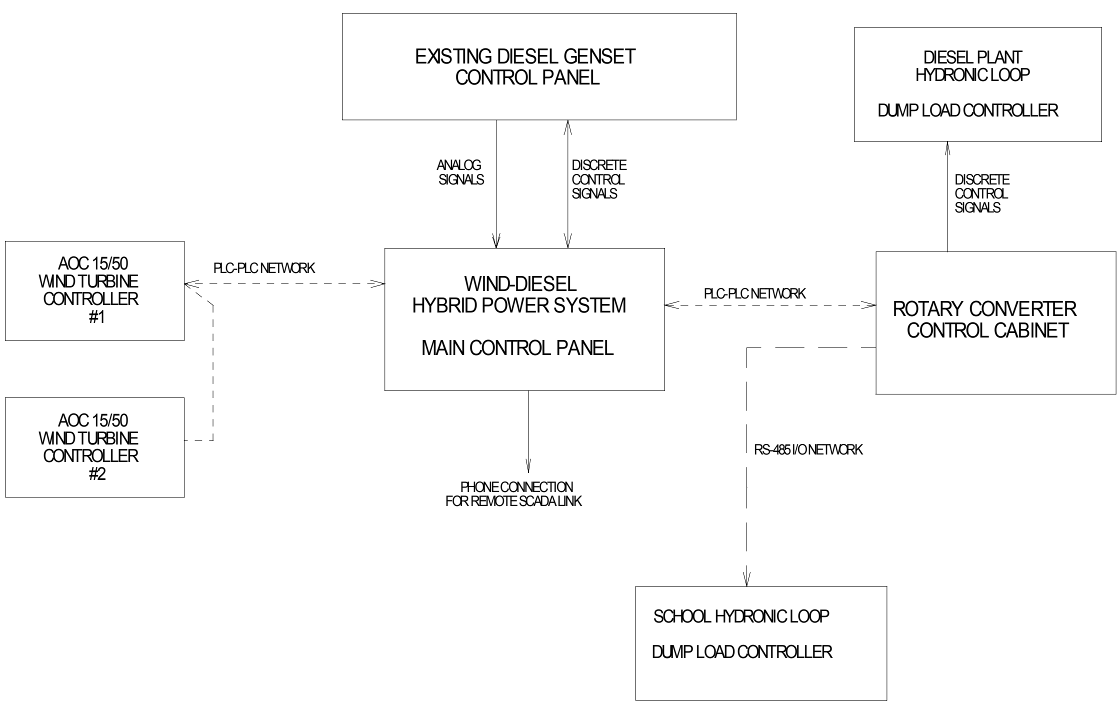

FIGURE 2. WIND-DIESEL SYSTEM COMMUNICATION AND CONTROL DIAGRAM

THE PRIMARY TASKS OF A POWER GENERATION SYSTEM

An automated wind-diesel hybrid power system controller is called upon to do a wide variety of tasks. These include such things as (1) automatic dispatch of the diesel generators to ensure proper loading and good operating efficiency, (2) operator notification of any warning or alarm conditions, (3) performance data logging to facilitate troubleshooting and maintenance, and (4) management of the secondary loads to ensure that excess power is directed where it is most needed. Fundamentally, however, the most critical tasks of the system are to provide good frequency and voltage regulation. Unless the system can provide good power quality, as measured primarily by frequency and voltage stability, it is not viable.

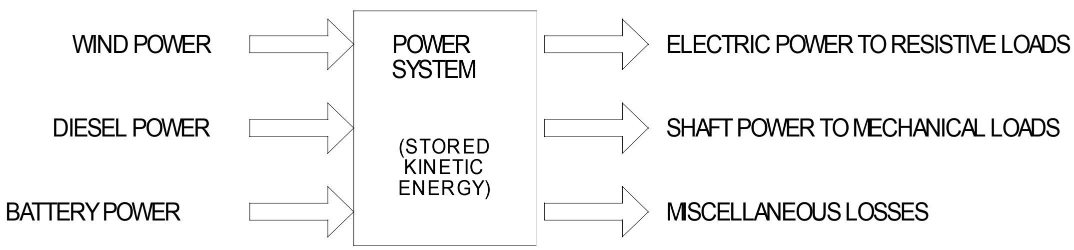

FIGURE 3 POWER FLOWS INTO AND OUT OF THE HYBRID POWER SYSTEM

Frequency Regulation

The entire power system, including all its generators, distribution wiring, and even motors present in the village load, can be thought of as one big electromechanical entity, as shown in Figure 3. Power flows into this system as power from the wind transferred to the wind turbine rotor, mechanical power developed in the diesel engines as a result of combustion, and electric power drawn from the battery. Power flows out of the system to consumer resistive loads, to consumer mechanical loads, to secondary loads, and as various mechanical and electrical losses. At any given moment, if more power is flowing into the system than out of it, the difference will be stored as an increase in kinetic energy of the rotating machines within the system, both generators and motors, that happen to be on-line at that time. The effect of any power imbalance in the system is expressed in Equation 1.

$$\sum P_{\mathrm{SOURCES}} - \sum P_{\mathrm{SINKS}} = \frac{d(K.E.)}{dt} = \frac{d}{dt}\sum_i J_i \omega_i^2 \qquad (1)$$

where P = active power (kW)
K.E. = kinetic energy of system
J = moment of inertia of rotating machine
ω = angular velocity of rotating machine

This increase in kinetic energy is manifested as an increase in rotational speed of the synchronous machines in the system and thus an increase in electrical frequency. The task of frequency regulation is essentially a problem of maintaining an instantaneous balance of the real power flowing into and out of the system.[1]

[1] This relationship of power imbalance to frequency change only applies to power systems in which the frequency is determined by the rotational speed of one or more synchronous machines in the system. In systems governed by a

Voltage Regulation

Analogously, regulating the AC voltage of the power system is a problem of maintaining an equilibrium between the source and sinks of reactive power (VARs) in the system. The induction generators of the wind turbines, transformers in the distribution system, and induction motors in the consumer load are all reactive power sinks. Power factor correction capacitors on the wind turbines or the distribution system are sources of reactive power. Synchronous generators, both on the diesel gensets and on the rotary converter, can either be sources or sinks, but generally they are supplying the reactive power demanded by the sinks.

Unlike the case of real power, where an imbalance can be absorbed by the system as a change in stored kinetic energy, there is no storage mechanism for "reactive energy", which only actually exists as a mathematical construct. The reactive power supplied by the sources is inherently equal to the reactive power absorbed by the sinks. This is expressed in Equation 2, in which the reactive power flows for each component are expressed as functions of voltage.

$$\sum Q_{SOURCES}(V_{AC}) - \sum Q_{SINKS}(V_{AC}) = 0 \qquad (2)$$

where Q = reactive power (kVAR)
V_{AC} = AC bus voltage

If the reactive power sources are unable to deliver the reactive power demanded by the sinks, the bus voltage will fall such that the equilibrium is maintained. With reactive power, the issue is not so much ensuring that equilibrium is maintained (which is automatic), but that the equilibrium occurs at the desired voltage level. On a synchronous machine, the function of the voltage regulator is actually to control the generator excitation such that the generator delivers the reactive power demanded by the load at the desired voltage.

THE OPERATING STATES OF THE WIND DIESEL SYSTEM

There are three devices subject to the direct control of the wind-diesel controller: the rotary converter AC machine, the rotary converter DC machine, and the secondary load controller (which actually consists of multiple distributed load controllers). Each of these devices has several different control modes associated with it. For example, the AC machine can be controlled to achieve any of the following:

- Match voltage with the AC bus (prior to synchronization)
- Share reactive power with the diesel generators
- Deliver a specified amount of reactive power to the grid
- Regulate AC bus voltage.

The power flow management algorithm determines the appropriate control mode for each of these three devices depending on the operating state of the power system.

The Wales wind-diesel hybrid power system involves multiple diesels and multiple wind turbines. In addition there is a power converter consisting of two separate rotating machines and a secondary load that is divided into "local dump load" and "remote dump load". Because each of these components may or

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voltage source inverter, the frequency is typically set by a crystal oscillator and does not vary. However, a similar situation exists in that any power imbalance then typically shows up as an increase or decrease in voltage on the AC and/or DC side of the inverter. The problem then becomes one of voltage control rather than frequency control.

may not be operating at any given time, there are a great number of possible system operating states. To develop a power flow management algorithm flexible enough to handle all possible operating states, one must identify a minimum set of key state variables that provide sufficient information to determine the appropriate control mode for each device.

Our top level state variable is the diesel status, because it has the biggest impact on how voltage and frequency is regulated. "Diesel ON" refers to the state where one or more diesel generators is connected to the bus *and* loaded (i.e. not in load or unload ramp). Conversely, "Diesel OFF" refers to the state in which all diesel generators are either disconnected from the bus or connected but not fully loaded.

Diesel ON State

The stand-alone diesel generator is designed to regulate the voltage and frequency on an isolated power bus. In a multiple diesel configuration equipped with automatic load sharing controls, the diesels collectively regulate frequency and share both the real and reactive power load in proportion to their respective ratings. Diesel gensets do an excellent job of frequency and voltage control provided that the real and reactive power load on them remains within their rated capacity and they are not subject to large reverse power transients. In the Diesel ON state, we allow the diesel generator(s) to perform their intended function of frequency and voltage control, and we control the rotary converter and/or secondary loads to maintain the diesel loading in a comfortable range. In summary, in Diesel ON state,

- The diesel generator(s) assume both frequency and voltage control
- Power flow to the secondary loads and/or energy storage is controlled to maintain diesel loading within a comfortable range
- The rotary converter ac machine is used to assist the diesel generators in meeting the var load, as necessary.

Diesel OFF State

In the Diesel OFF state, the only synchronous machine left on the system is the AC machine of the rotary converter. The rotational speed of the rotary converter will establish the grid frequency. As with the diesel generator, the voltage regulator on the rotary converter AC machine controls the field current so as to maintain the desired AC bus voltage. Frequency is controlled by modulating power flow to the secondary load or battery, depending on factors to be discussed below.

System Sub-States

Diesel status is only the first of the system state variables that are used in determining the appropriate control mode for the various system components. The others reflect the state of readiness of the other system components and the nature of the instantaneous real power imbalance on the system. They are embodied in the following questions:

1. Is the (rotary converter) AC machine on line and ready?

   Just as with the diesel generator, for the AC machine to be available to perform its control function, not only must its contactor be closed, but it must also not be in an unload ramp, preparing to go off-line.

2. Is the DC machine on line and ready?

   Similarly, the DC machine is only available for control when its contactor is closed and it is not in a transitional state.

3. Is there instantaneous excess wind power?

   In the case where there is excess wind power, secondary (or "dump") load may be used to provide frequency control. As long as there is excess wind power, this works fine, but suppose the wind suddenly drops, resulting in a power deficit. As wind power drops, secondary load will be rapidly removed in an attempt to maintain grid frequency. Once it has all been removed, the ability to control frequency is lost. The system must switch immediately to frequency control by the DC machine.

4. Is the battery "full"?

   This question refers to whether the present level of current into the battery can be sustained. It is actually several questions rolled into one. With a "yes" answer to any one of them, the battery is considered "full".

   - Is the battery at a high state of charge (i.e., actually full)?
   - Is the DC charging current limit of the rotary converter reached?
   - Is the charging voltage limit of the rotary converter reached?

Note that the state variables presented above are concerned only with whether the various system components are on line and ready at a particular moment in time, not when and why they are brought on line. The criteria by which individual diesels, wind turbines, and the rotary converter AC and DC machines are turned on and off are the subject of a whole suite of dispatch algorithms not covered in this paper.

THE POWER FLOW MANAGEMENT ALGORITHM

The power flow management algorithm is presented in flow chart format in Figure 4. Each decision block represents one of the state variables described above. Each branch in the decision tree specifies the control mode of the devices actively participating in voltage and frequency control in the corresponding state. Note that each branch loops back to the beginning of the algorithm, since any of the key state variables can change at any moment.

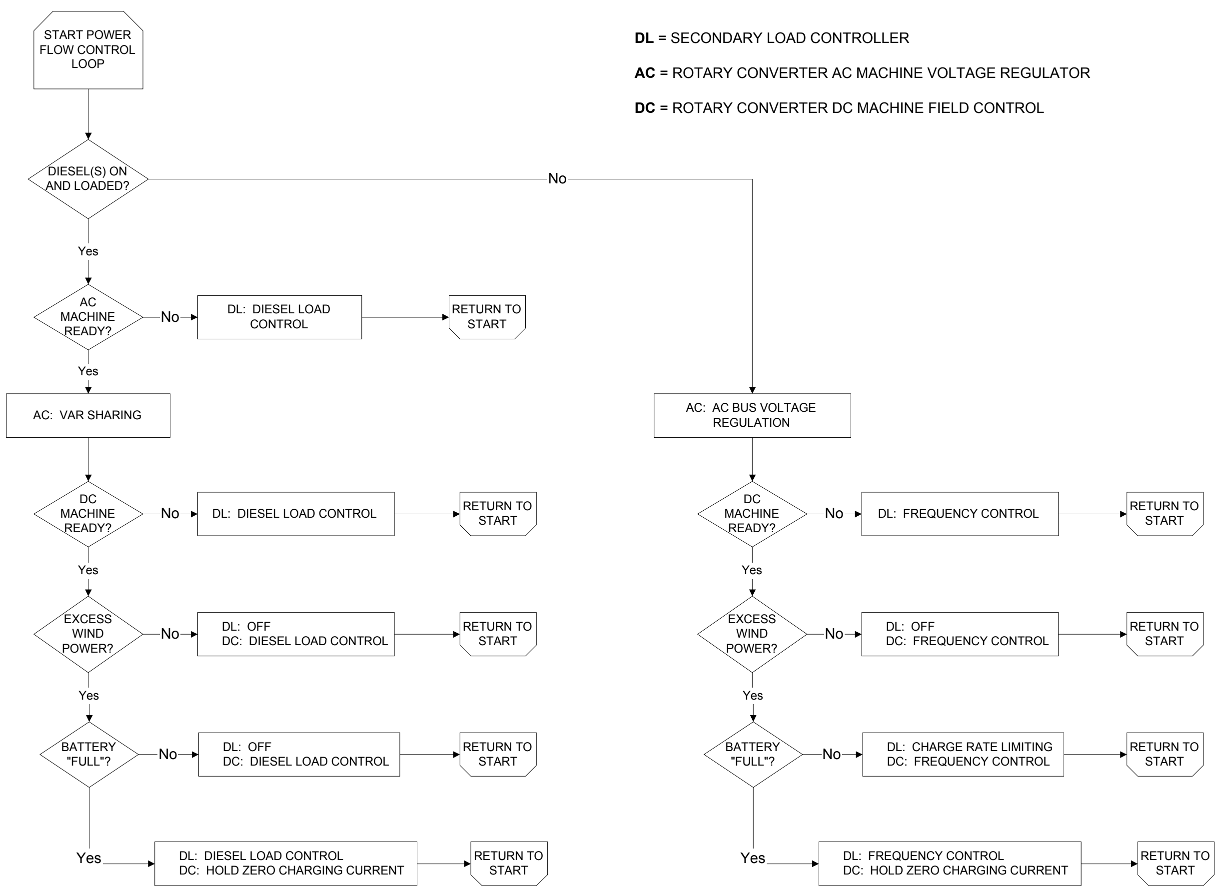

FIGURE 4. POWER FLOW MANAGEMENT ALGORITHM

PERFORMANCE REQUIREMENTS OF THE CONTROL SYSTEM

In the Wales wind-diesel control system, the loop shown in Figure 4 is executed approximately once every 20 milliseconds (ms). A short loop interval is necessary in order to detect and immediately respond to changes in component status. For example, when the last diesel goes off line, the rotary converter must step in immediately to control the grid frequency and voltage. If the transition is too slow, unacceptable deviations of either voltage or frequency could result.

When a change in state occurs that calls for a change in the control modes of one or more devices, it is important that the mode changes occur seamlessly, without causing discontinuities in power flow, which would be manifested as frequency or voltage transients on the line. This requirement is not expressed in the flow chart, but it is an important part of the design of the various control modes and requires careful application of bumpless transfer techniques.

CONTROL CHALLENGES OF A HIGH-PENETRATION WIND-DIESEL SYSTEM WITH ENERGY STORAGE

Compared to conventional power generation systems, where short-term load variations are typically small and the principal power source is dispatchable on demand, high penetration wind-diesel power systems are challenging to implement. The wind power input to the system is stochastic in nature and highly variable, particularly at gusty sites. At the Wales project, there will be times when the wind power exceeds 200% of the village load, with short-term variations as large as the load itself. There is also the fact that on small isolated power grids, single loads tend to represent a larger percentage of the total load. Starting even a small industrial motor, for example, could have a perceptible impact on the system. The variability in the wind and the variability in the load combine to yield rapid and high amplitude fluctuations in the net load, which is the difference between the primary load and the instantaneous wind power. The net load represents the power that must be supplied by the diesel generator(s) and/or energy storage, or if it is negative, must be absorbed by secondary loads to maintain the real power balance discussed above.

Low system inertia is another factor that contributes to the challenge of providing tight frequency regulation in wind-diesel hybrids. The rotating mass contained in a typical isolated wind-diesel hybrid system is disproportionately smaller than that of large utility-scale power systems. Whereas the time constant in a utility system for the frequency to respond to a change in load is measured in seconds or even minutes, it is measured in tenths of a second for the hybrid system. The actual PID control loops used to control power flow in the secondary loads and in the rotary converter must provide very fast response. Because of the requirements for speed and automatic control mode switching, AC-based[2] wind-diesel hybrid systems require active computer control systems to provide stable operation and good power quality.

CONCLUSIONS

The Wales, Alaska, project will demonstrate the feasibility of retrofitting an existing village diesel plant to create a high-penetration wind-diesel system that achieves a large reduction in diesel fuel consumption and run time and that uses all available wind energy in a productive manner. The Wales system consists of nine active power system components (three diesel gensets, two wind turbines, two secondary load controllers, an AC synchronous generator, and a DC motor). The variable status of each of these power components gives rise to many possible system operating states. The control system must respond rapidly to changes in system operating state and smoothly transition among a variety of control modes. The controller must regulate both real power to provide stable frequency and reactive power to provide stable voltage.

Implementing such systems requires not only controls expertise but also a detailed knowledge of the individual system components and how they interact. For example, some wind turbines have a large inrush current on synchronization. Some turbines have no inrush and can control their own power factor. The power converter interface to the energy storage must be designed to operate in a way that is compatible with the wind turbine requirements. As another example, some secondary loads have a very fast response (e.g., electric resistance heaters) and some a slow response (e.g., water pumps, ice makers).

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[2] In AC-based systems, the wind turbine generators are typically of the induction type and connected to the local AC distribution system. These are in contrast to small DC-based hybrid systems where wind turbines, and often photovoltaic panels, are connected to a DC bus, in parallel with a battery.

A hybrid system controller algorithm would need to take these differing characteristics into account in order to achieve acceptable frequency control. Because of the considerable impact of individual component characteristics on overall system operation, it appears that in the near term, the design of hybrid power control systems will be fairly specific to a particular power system architecture. Only after considerably more high penetration wind hybrid systems operating experience has been obtained, and the many control issues posed by various generation, load, and storage devices are better understood, will it be possible to design generic hybrid system controllers capable of adapting to a wide variety of components and system architectures.

Regarding the cost of wind hybrid power systems, it is misleading to think of the nongeneration hybrid system components (system controller, power converters, energy storage, secondary loads) as mere accessories to either the wind turbines or the diesel power plant. These components typically represent 25%-50% of the equipment cost of the system, not including the cost of the diesel plant and distribution system, which is pre-existing in many cases. Wind hybrid project promoters, developers, and potential customers often underestimate these costs when considering a project.