A Fuzzy Controller for a Hybrid Wind/Diesel System with Storage

by

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LIST OF SYMBOLS USED

C_{BW}	battery wear cost, \$/kWhr
C_D	cost of diesel generated power, \$/kWhr
C_F	diesel fuel cost, \$/liter
C_T	total operating cost
E_D	energy discharged from batteries, kWhr
F	diesel generator fuel consumption rate, liters/hr
F_i	incremental diesel fuel consumption rate, liters/hr
F_0	diesel generator fuel consumption at no load, liters/hr
P	diesel generator electrical power output, kW
P_F	frugal discharge threshold, kW
P_{OPTO}	optimal fixed discharge threshold, kW
P_r	rated power of diesel generator at full load, kW
P_W	wind turbine electrical power output, kW
$\mu(x)$	truth value
V_W	wind speed, km/hr
$V_{W(AVG)}$	yearly average wind speed, km/hr

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I dedicate this work to my wife, Claudia, and to my children, in thanks for their unending patience and support.

ABSTRACT

For remote power systems using a combination of wind energy and diesel power, large storage batteries may be used to reduce diesel fuel consumption. In order to assess the feasibility of incorporating storage batteries, potential savings in fuel costs must be weighed against the capital equipment costs associated with the storage system. In such a cost-benefit analysis, the dispatch strategy used to control the system is critical in determining the amount of cost savings, and hence the feasibility of storage.

This thesis is a study of various control strategies that may be used in the dispatch of stored wind energy in a remote wind/diesel power system. A theoretical ideal dispatch strategy is presented as a means of determining the maximum savings possible. Several simple dispatch strategies are discussed. A fuzzy discharge controller that uses battery state of charge and wind speed forecasts to optimize battery discharge is presented. Computer simulations are used to evaluate the performance of the various control strategies, and results are compared.

A case study of a typical small wind/diesel system is presented. It is shown that the reductions in operating costs achieved by using storage can be significantly increased using the fuzzy discharge controller. The role of wind speed prediction is examined and practical implementation issues are addressed. Implications for the general feasibility of large-scale storage are discussed.

1. INTRODUCTION

1.1 The Role of Wind in a Remote Power System

In many locations around the world, electricity supply requirements cannot be met by utility grids due to the remoteness of the communities. Typically in such cases, one or more diesel generators are used to generate the required electricity. The cost of this electricity is very high because such systems cannot take advantage of the economies of scale that characterize large-scale power generation. The major operating cost of a small diesel powered system is the cost of purchasing and transporting diesel fuel.

In recent decades, rising fuel prices and growing concern for the environment has prompted interest in using renewable energy sources to augment power generation in remote locations. The primary renewable energy sources that have been investigated have been solar energy and wind energy. A remote power generation system using diesel generation and one or more sources of renewable energy is often referred to as a "hybrid" power system. Communities in Northern Canada, Australia, the Greek Islands, and Scandinavia are among the locations suggested as suitable for benefiting from the installation of hybrid power systems using wind energy (Lynette & Gipe, 1994).

A great deal of research has been conducted into the economics of including one or more wind turbine generators in a remote power system. In such a hybrid system, wind energy is used to reduce the net load (system load minus renewable power) on the diesel generators in order to reduce fuel consumption. In general, results indicate that for locations with high wind speeds, reductions in diesel fuel costs more than offset the capital equipment costs of the wind turbines (Infield, Slack, Lipman, & Musgrove, 1983).

1.2 Control of a Hybrid Power System

There are a number of control issues that must be considered when wind energy is introduced into an isolated power system. Wind power is dependent on wind speed, and wind speed is known to be highly random in nature (Van der Hoven, 1956). The fluctuations in wind energy supply give rise to particular control considerations. There are two distinct levels in the control of a hybrid power system:

1) dynamic control, which deals with control of the frequency and magnitude of the output voltage of the system, and
2) dispatch control, which deals with the flow of energy in the system from the various sources to the load.

The dynamic control problem deals with maintaining the system output within acceptable operating limits, and addresses performance on a time scale in the order of seconds and fractions of a second. The dispatch control problem is concerned with controlling the flow of energy, on a time scale of minutes to hours, in such a way as to optimize system performance in terms of operating costs.

One useful means of characterizing a wind/diesel system is the wind/load ratio (WLR). This is the ratio of average wind power at the site to average system load, usually averaged over the period of one year. A high WLR ("high penetration") signifies a site with a high component of wind energy relative to diesel generator energy. Research has shown that the amount of fuel savings is greatest when wind penetration is high enough to allow the diesel generators to be turned completely off for extended periods of time (Lipman, 1984). Doing so eliminates the fuel consumption that is required to keep the diesel generators rotating even when they are producing no output power.

Systems with high wind penetration, however, are more difficult to control due to the random nature of wind speed. The wind speed may be high enough that the entire load can be met by the wind turbines, allowing the diesel generators to be turned off. If the wind speed decreases such that the load then exceeds the wind energy, diesel generators must be turned on again. This can lead to a high number of diesel stop/starts, with possible detrimental effects on the diesel generator (Contaxis, & Kabouris, 1991). An important aspect of the dispatch control strategy of a hybrid system is to take advantage of the high fuel savings possible in shutting down the diesel generators, while avoiding an excessively high number of diesel stop/starts.

1.3 The Role of Storage in a Hybrid Power System

Much recent research has focused on the addition of energy storage capability to a hybrid energy system. In addition to storage batteries, some of the other forms of storage investigated have been flywheels (Davies, Jefferson, & Mayer, 1988), superconducting magnetic storage (Tripathy, Kalantar, & Balasubramanian, 1991), and pumped storage (Sinha, 1991). In such investigations, storage size is often referred to in terms of the amount of time the storage capacity alone could power the system at average load.

Energy storage in a hybrid power system can be used for a number of purposes. The most commonly proposed are:

1) to reduce the number of diesel stop/starts by using storage to meet high frequency fluctuations in the net load caused by wind turbulence;
2) to store excess wind energy so that it may be used at a later time to reduce fuel consumption;
3) for cycle-charging in order to reduce diesel running time.

Research has shown that in a typical hybrid system the addition of 2 to10 minutes of energy storage capacity is sufficient to reduce the number of starts to an acceptable number (Watson, 1987). In such a scheme, the diesel generator would be used to meet the average net power requirements, while the storage would meet the random fluctuations caused by wind turbulence and, to a lesser degree, load variations. A small amount of storage capability used in this manner is considered to be "short-term" storage. Flywheels or battery storage are considered to be the most practical methods of implementing such short-term storage.

The use of "long-term" storage (more than a few minutes of storage capacity) can allow for more flexibility in the dispatch control of the hybrid system. In high wind penetration systems, there are times when the wind-generated power exceeds the system load requirements. This could happen due to low system load (in the early hours of the morning, for example), high wind speed, or both. The question of what to do with the excess energy then arises. There are several possible alternatives. One option is to dump the excess energy, to a resistive load, for example, essentially wasting it. Another possibility is to use the excess energy to power non-essential loads, such as domestic water heating. This form of control strategy is referred to as load control. A third alternative is to store the excess energy using a long-term storage device.

Storage batteries (lead-acid or nickel-cadmium) are the most commonly used forms of long-term energy storage in wind/diesel systems (Little, 1995). Storage batteries have the advantage of being a proven technology and are readily available. However, as Lipman (1988) has observed, the cost of storage batteries is high and the use of batteries gives rise to a number of practical problems. Additional electronic circuitry (an inverter and a converter) is necessary when using DC storage batteries on an AC power system. This increases the associated capital equipment costs. Inverters can introduce harmonics, distorting the system power output. Because storage batteries require maintenance and perhaps special housing, they may not be well suited to remote locations (Saulnier, Reid, & Yves, 1993). Due to these and other considerations, the feasibility of incorporating battery storage in a hybrid power system is the subject of on-going study.

1.4 Dispatch Strategies

In a hybrid wind/diesel power system with long-term storage, there are three possible sources of energy – wind turbines, diesel generators, and storage batteries. The dispatch strategy of the system controls the flow of energy between these devices and to the load. There are two separate aspects to the dispatch control of the system: the battery charging strategy and the battery discharging strategy.

1.4.1 Battery Charging Strategies

The two possible sources of energy for battery charging in a hybrid system are excess wind energy and excess diesel generator energy. As previously mentioned, at times when wind power exceeds the system load, the excess power may be used to charge the storage batteries (provided they are not already fully charged). Opportunities for this type of charging occur frequently in systems with high WLRs.

The other possibility is to use the diesel generator to charge the batteries. This technique is known as "cycle charging." When the net load on the diesel generators is low, the diesel power output can be increased, with the excess power produced being used to charge the storage batteries. The stored diesel energy could, at a later time, be used to meet the net load, thereby allowing the diesel generators to be shut off. The advantages of cycle charging are that it allows the diesel generators to operate at a higher power output, where it operates more efficiently; and that it allows for longer diesel shut-down periods, thus reducing the rotating costs associated with the diesel generators.

However, the economics of using diesel power to charge the batteries are not nearly as favorable as using excess wind energy. Whereas producing excess wind energy is essentially free in terms of operating costs, the production of excess diesel power increases fuel consumption. The effectiveness of various battery charging strategies, including various forms of cycle charging, has been extensively investigated by Barley (1996). As a result of his economic analysis, Barley concluded that cycle charging can only result in reduced operating costs if storage battery costs are low (relative to diesel fuel costs), and if the efficiency of the storage system is high. Otherwise, a load-following dispatch strategy, wherein only excess wind power is used to charge the batteries, is optimal.

1.4.2 Battery Discharging Strategies

Likewise there are several options in how battery-stored energy can be used. For example, battery power could be used to augment the diesel power in meeting the net load so as to reduce diesel fuel consumption. However, as previously discussed, maximum savings are achieved when the diesel generators can be shut off. Thus it is more effective to use battery power to augment wind power in situations where this will allow the diesel generators to be shut down completely. The role of the discharge strategy, then, is to control when the net load will be met using stored energy (if available) and when diesel generated power will be used. Using the terminology of Nayar (1989), the system can be considered a form of "switched hybrid" system as shown in Figure 1.

As will be seen, there are a number of possible strategies for dispatching stored energy in such a system. The optimization of this process in terms of minimizing operating costs is the focus of this thesis.

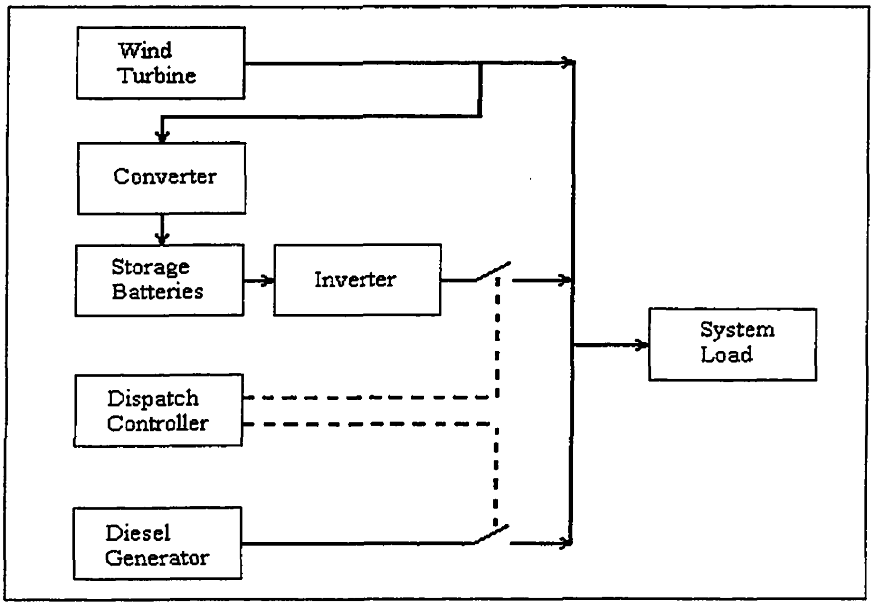

Figure 1 - Block diagram of hybrid power system

1.5 The Role of Prediction in a Hybrid Power System

As has been discussed, the random nature of wind speed contributes to difficulties in controlling hybrid wind/diesel systems. As a consequence, extensive research has been conducted in the area of wind speed prediction. Kalman filters (Bossanyi, 1985) and, more recently, neural networks (Kariniotakis, Stavrakakis & Nogaret, 1996) have been among the experimental techniques aimed at implementing accurate prediction of wind speed. Indeed, the perceived necessity of some type of wind prediction has been considered by some as mitigating against the inclusion of wind capacity in remote power systems (Reid, 1992).

In contrast to this trend, Barley (1996) in his study of dispatch strategies, proposed an "Ideal Predictive Strategy" as a means of evaluating the potential value of wind speed prediction in dispatch control. He found that some simple non-predictive strategies performed just as well as the ideal predictive one. He explained these finding saying

> The reason for this may be understood intuitively as follows. The role of prediction in the dispatch scheme is to avoid situations where energy that was stored in the battery by the diesel generator is eventually wasted, because the same charging could have been accomplished by the WTG before the energy is needed. . . . Thus efforts to develop predictive controllers for this type of system are not supported by this study. (p. 77)

However, Barley's study focused primarily on determining optimal battery charging strategies for wind/diesel systems. In terms of battery discharge strategies, the extent of his study was to recommend the use of what he called the "Frugal Discharge Strategy." The problem with Barley's conclusion regarding prediction is that there are other roles prediction can play in addition to the limited role described above. As will be shown, there are several alternative discharge strategies that can give better results than the Frugal Discharge Strategy proposed by Barley. These other strategies are based on the judicious dispatch of stored energy so as to minimize operating costs in a manner he did not address. Some of these strategies utilize wind speed prediction. Barley's Ideal Predictive Strategy, which he used as a benchmark for evaluating other strategies, uses the Frugal Discharge Strategy. It cannot be considered truly ideal because performance can be improved by using other discharge strategies.

In this study, the role of wind speed prediction in optimizing battery discharge will be considered and the practical aspects of implementing such prediction will be addressed.

1.6 Scope of Research

This study is an investigation of discharge strategies in a hybrid wind diesel system with several hours of battery storage. The focus is on systems in which it is not economical to charge the storage batteries using diesel generated power; rather it is assumed that the batteries are charged only by excess wind power. Thus the analysis is of the optimal use of stored wind energy in a hybrid system.

A system with no load control is assumed and a storage capacity of about 3 hours is used for case studies. Several discharge strategies are presented and computer simulations are used to compare system performance in terms of fuel costs, battery wear costs, diesel starts, and other criteria. A theoretical Ideal Discharge Strategy is proposed as a means of gauging the effectiveness of the various practical discharge strategies. Finally, fuzzy logic is used in implementing an improved discharge strategy for this type of hybrid system.

Hourly samples of wind and load data are used, with the assumption that stability of system frequency and voltage are maintained by a dynamic control layer beyond the scope of this study.

It is envisioned that the results obtained in this analysis will be useful in assessing the cost effectiveness of long-term battery storage in a hybrid wind/diesel system.

1.7 Simulation Software

There are available a number of software packages designed specifically for simulating wind/diesel systems. Hybrid2 from the University of Massachusetts is one of the most popular. However these programs could not be used in this study because they do not allow for simulation of the new control strategies presented here. Nevertheless, site data from the Hybrid2 package was used in verifying the performance of the fuzzy controller design.

The simulations carried out in this study were performed on a Pentium 233 computer using MatLab 5.0 software and Matlab's Fuzzy Toolbox . The Fuzzy Toolbox constitutes an existing fuzzy logic library that implements standard fuzzy logic procedures in a user-friendly environment. This feature, together with MatLab's powerful graphing capabilities and the software's popularity in engineering circles, were the reasons this software was selected. (Appendix A contains a listing of the code for relevant procedures used in the simulations.)

2. REVIEW OF MODELS

As the focus of this study is the issue of battery discharge strategies in a hybrid power system, it is necessary to consider those aspects of the system that are relevant to determining an optimal operating strategy. Thus, factors such as capital equipment costs and routine system maintenance that are not affected by the operating strategy will not be addressed. This section describes the models and simplifying assumptions that are used in the analysis and case study to follow. Relevant operating cost considerations of the various system components are presented and discussed.

2.1 Wind Turbine

Wind turbines are designed for a particular maximum power output and average wind speed. In this study, the characteristics of the Enertech 40/44 wind turbine are used in all simulations. This machine incorporates a 480V, 40kW induction generator. The power characteristics are approximated (Little, 1995, p. 28) using the piecewise function

$$\begin{aligned} P_W &= 0 && \text{for} \quad 0 \le V_W < 19 \\ &= 5.589 \times 10^{-4}\, V_W{}^3 && \text{for} \quad 19 \le V_W < 35 \\ &= 40 - 0.0401(V_W - 55)^2 && \text{for} \quad 35 \le V_W < 54 \\ &= 40 - 0.15(V_W - 54) && \text{for} \quad 54 \le V_W < 85 \\ &= 0 && \text{for} \quad V_W \ge 85 \end{aligned} \tag{2.1}$$

where:

P_W is wind turbine electrical power output, kW and

V_W is wind speed, km/hr

At speeds below 19 km/hr, this turbine produces no electrical power. At speeds above 85 km/hr, the turbine shuts down and stops rotating as mechanical damage could otherwise result. (The power characteristics are illustrated in Figure 2-1.)

The 40 kW power rating describes the maximum power output capability of the wind turbine. The average power output, of course, depends upon the wind profile at the site. As a rule, average power output is about a third of rated power (Lipman, 1988).

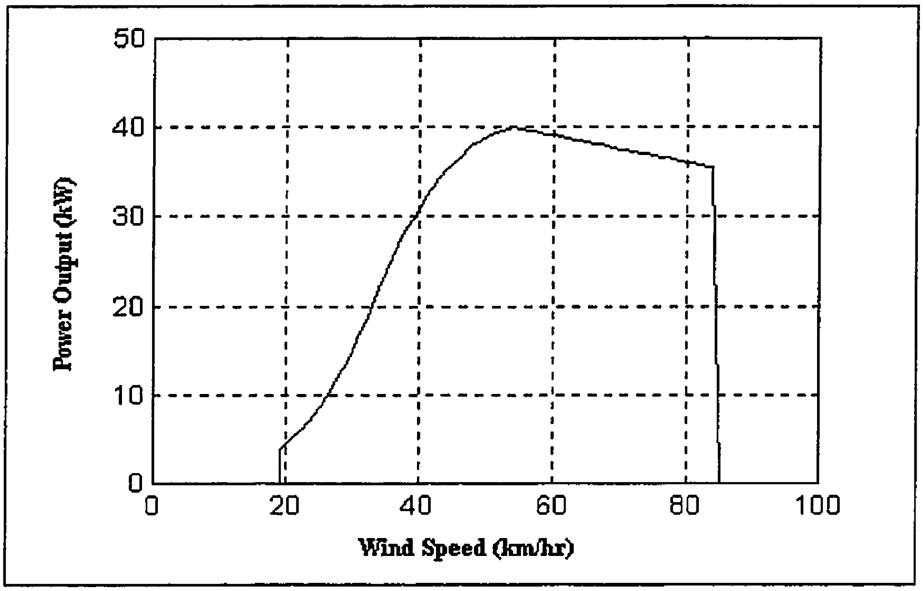

Figure 2-1 Power characteristics of Enertech 40/44 wind turbine

2.2 Diesel Generator

Though the fuel consumption characteristic of a typical diesel generator is somewhat quadratic in nature, the linear function of equation (2.2) is used as a simplified model.

$$F = F_0 + F_i P \tag{2.2}$$

where:

F is diesel generator fuel consumption rate, liters/hr

F_0 is diesel generator fuel consumption at no load, liters/hr

F_i is incremental diesel fuel consumption rate, liters/hr

P is diesel generator electrical power output, kW

Skarstein and Uhlen (1989) have suggested that the fuel consumption parameters can be approximated as

$$F_i = 0.246 \text{ liters/kWhr} \tag{2.3}$$

$$F_0 = 0.08415 \text{ x } P_r \text{ liters/kWhr} \tag{2.4}$$

where P_r is the rated power of diesel generator at full load, in kilowatts. For a 100 kW diesel generator, these assumptions yield the fuel consumption characteristic of Figure 2-2.

Because approximately 25% of full load fuel consumption is required to keep the generator running at no load, the diesel generator is particularly inefficient at low loads.

The cost per kWhr of diesel generated power is found by dividing the fuel consumption costs by the generated power yielding

$$C_D = C_F\,(F_i + F_0/P) \tag{2.5}$$

where

C_D is cost of diesel generated power, \$/kWhr, and

C_F is diesel fuel cost, \$/liter

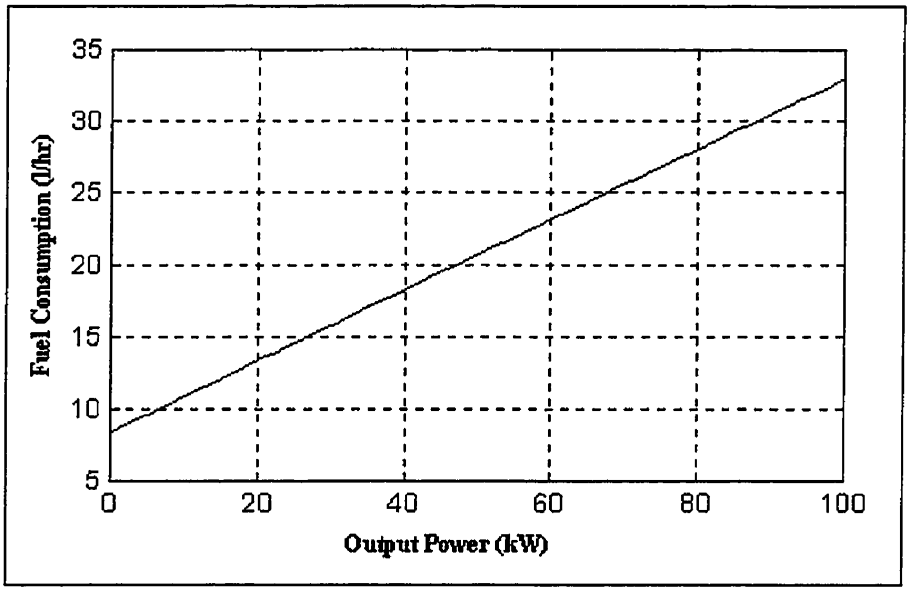

Figure 2-2 Diesel generator fuel consumption characteristics

Figure 2-3 illustrates the cost of diesel energy per kWhr for a fuel cost of \$0.26/liter. At high loads, the diesel operates most efficiently, while the cost per kWhr of diesel generated energy becomes very high as the load is decreased towards zero.

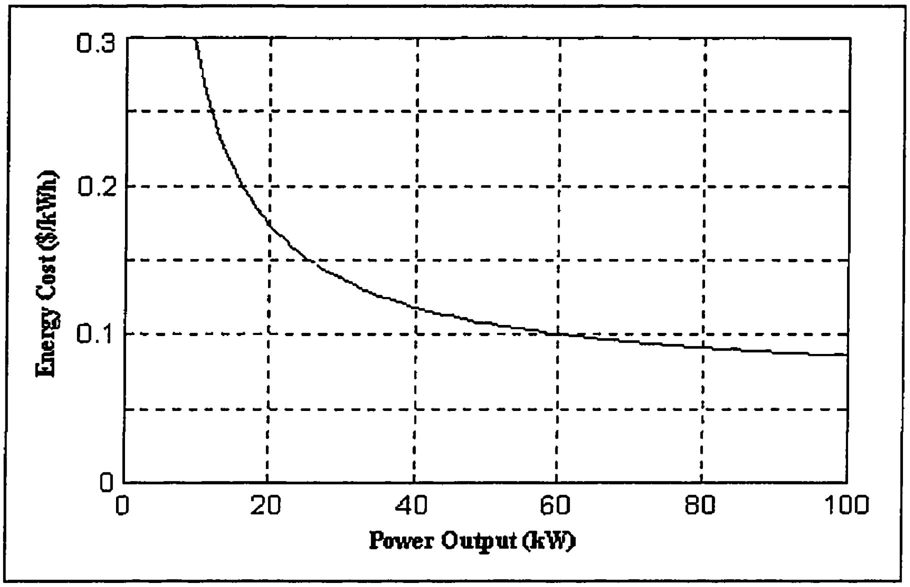

Figure 2-3 Diesel energy costs for C_F = $0.26/liter

2.3 Storage Batteries

Although nickel-cadmium batteries have several favorable characteristics, the lead-acid battery is more commonly used in hybrid power systems due to its lower capital costs (Linders, 1989). Because the expected lifetime of lead-acid batteries is usually short compared to the other components of a hybrid power system, and because battery wear is related to the operating strategy, the cost associated with battery replacement is considered an operating cost.

2.3.1 Battery Wear Costs

The two main factors that determine the life of lead-acid storage batteries are ambient temperature and depth of discharge (Spiers & Rasinkoski, 1996). Ambient temperature is not dependent on the dispatch strategy of the system, and its effects will be assumed to be negligible for this study. However, because the dispatch strategy determines the frequency and depth of battery discharge, the costs associated with depth of discharge are important to consider.

Lead-acid storage batteries have a limited lifetime that depends upon the number of cycles and the depth of each discharge cycle. Figure 2-4 shows a typical relationship (Nayar, Lawrance, & Phillips, 1989) between total discharge cycles and depth of discharge (DOD) for lead-acid batteries. At high discharge depths, the number of discharge cycles achievable is relatively low, while as the discharge depth is decreased, the number of cycles increases.

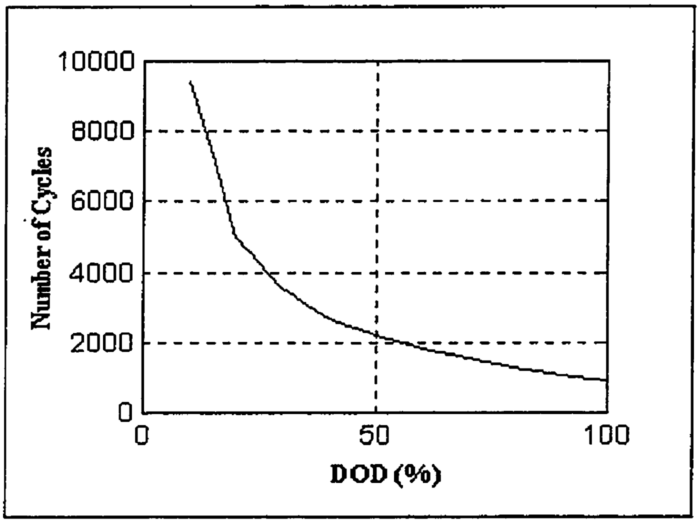

Figure 2-4 Battery discharge cycles versus depth-of-discharge

To consider the total amount of energy a battery is capable of discharging over its usable lifetime, the product of discharge depth and number of cycles can be taken. For the battery characteristic of Figure 2-4, the total amount of discharged energy is fairly constant regardless of the discharge depth (see Figure 2-5). In studying a number of lead-acid battery types commonly used in hybrid power systems, Barley (1996) concluded that most have a relatively linear characteristic similar to Figure 2-5, over are fairly large range of discharge depths.

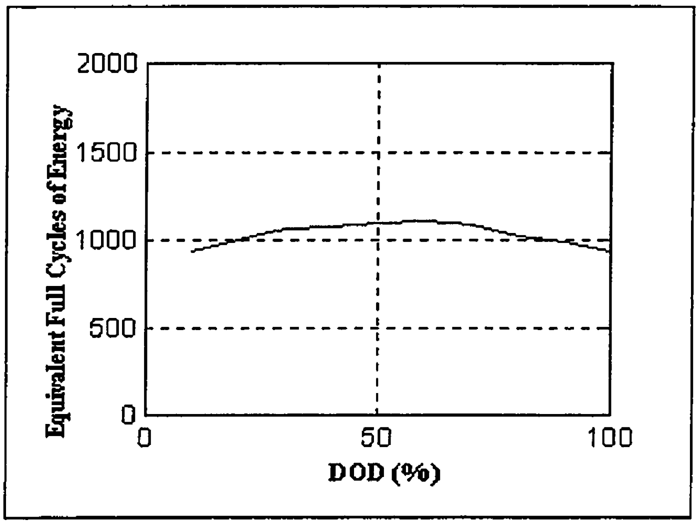

Figure 2-5 Total battery energy versus depth-of-discharge

Based on this analysis, a simplifying assumption can be made in ascribing a battery wear cost to battery usage. In this study, it is assumed that the storage batteries have a fixed number of equivalent full cycles to failure. Every time energy is withdrawn from the batteries a cost is incurred in terms of battery wear. This battery wear cost, C_{BW}, can be determined by dividing the capital cost of the batteries by the total amount of energy the batteries are capable of handling over their entire lifetime:

$$C_{BW} = \text{(battery purchase cost per kWhr)/(number of full cycles expected)} \qquad (2.6)$$

For example, if storage batteries cost \$120 per kWhr and the batteries are rated for 1000 cycles at full discharge, then the battery wear cost for the energy retrieved from the batteries would be $C_{BW} = \$120/1000 = \$0.12/\text{kWhr}$.

2.3.2 Battery Storage Size

There is no straightforward method of determining the optimal amount of long-term storage capacity for use in a hybrid wind/diesel system. Indeed, the conclusions of this study may be helpful in carrying out such a cost-benefit analysis. The marginal cost savings achieved by the addition of long-term storage have been shown to diminish as storage capacity increase (Lipman, 1988). Several studies (for example, Infield, Slack, Lipman, & Musgrove, 1983, and Little, 1995) have found that a storage size in the order of several hours may be optimal. For this reason, a storage capacity of 150 kWhr, representing about three hours of capacity, was chosen for the case studies presented here. The implications of storage size on the conclusions drawn are addressed in a later section of this report.

Normally it is recommended that storage batteries not be discharged to less than a specified minimum level to avoid damaging the batteries (Musgrove, 1987). Typically this level is 30% to 50% of rated capacity. In keeping with this recommendation, it will be assumed throughout the discussions to follow that "storage capacity" refers to usable storage capacity above such a minimum discharge limit. Thus, the actual physical storage capacity may be somewhat greater than the usable storage capacity discussed.

2.4 Wind Data

The simulations in this work are based on the study of a one-year period. The wind data used is from the Atlantic Wind Test Site located in Prince Edward Island, Canada. This test site is a research center dedicated to the study of hybrid wind/diesel systems for isolated locations. Like many other wind test sites around the world, the Atlantic Wind Test Site records wind speed data on an hourly basic. A one-year wind profile of hourly average wind data recorded at the test site is used in this study. The mean wind speed is 6.9 m/s with a peak of 23 m/s and a standard deviation of 3.6 m/s.

The wind data exhibits seasonal variations as illustrated in Figure 2-6. The site is characterized by relatively high winds during the winter months, and low winds during the summer. For example the mean wind speed for the month of January is 8.2 m/s whereas that of May is 4.9 m/s.

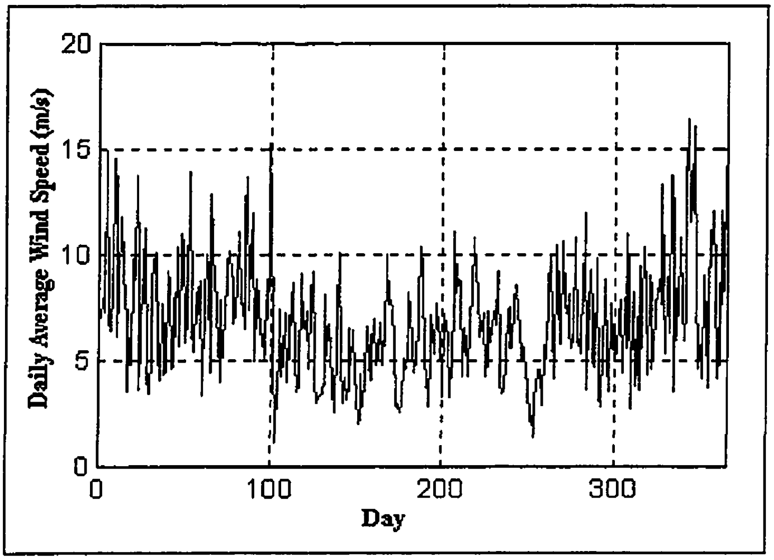

Figure 2-6 Seasonal variations in daily average wind speed

2.5 Load Data

The load data is comprised of 8760 data points (1 year) of hourly average system load. This data is used at the Atlantic Wind Test Site to simulate a village load. It was obtained from actual measurements at a remote location in northern Canada where a diesel system is currently used to meet the load requirements. The raw data had a peak of about 1200 kW and has been scaled to represent a small system with a mean load of 55 kW and a peak of 89 kW. Figure 2-7 shows the profile of load fluctuation for a typical day. The load data also exhibits some seasonal variation with the highest demand being during the winter months.

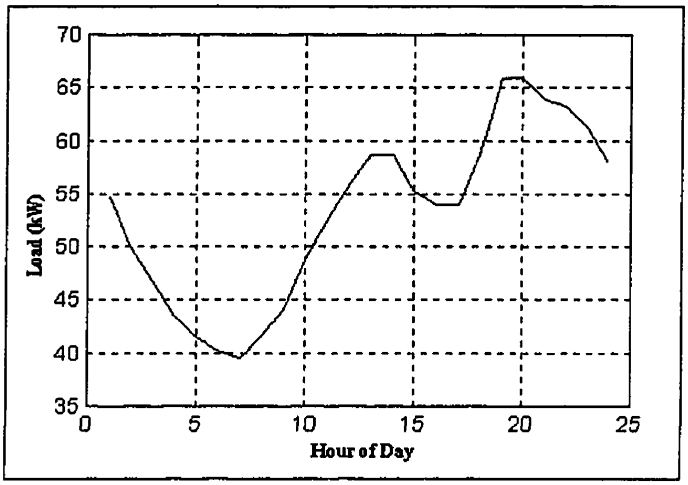

Figure 2-7 Typical daily variation in load

2.6 Simplifying Assumptions

In order to simplify the analysis to follow, several assumptions are made with regard to the system and its components. These assumptions are presented and discussed in this section.

2.6.1 Storage Efficiency

Like all storage devices, batteries systems suffer from inefficiencies. Each time energy is stored in a battery and retrieved, some losses occur. Additionally, incorporating battery storage in a hybrid system requires the use of several other components. A converter or rectifier is required to change the AC power to DC for storage in the batteries. An inverter is required to change the DC power from the batteries back to AC power for the load. Both the inverter and the converter suffer losses, degrading the overall efficiency of the storage system.

In this study, a round-trip efficiency factor of 80% is assumed for the entire storage system. The impact of this assumption will be discussed in a later section.

2.6.2 Battery Self-discharge

Storage batteries are known to exhibit a characteristic of self-discharge whereby the batteries lose some amount of stored energy over time as a result of internal chemical reactions. A loss factor can be assigned to represent the self-discharge loss for a one-hour period. In this study an hourly self-discharge factor of 0.9999 is assumed. This means the storage batteries would lose about 7% of their stored energy due to self-discharge alone in a one-month period.

In carrying out the simulations that follow, other self-discharge factors were tried with no significant effect on the conclusions drawn. Only for unrealistically low self-discharge factors (such as 0.9) did this effect have any significant impact on the results.

2.6.3 Storage System Power Limitation

Storage batteries as well as rectifiers and inverters are limited in their continuous power handling capabilities. In this study, a limitation of 50 kW is assumed for these devices. This limitation was found to have no significant impact when compared to an analysis where such limitations were completely disregarded.

2.6.4 Diesel Engine Starts and Maintenance Costs

In analyzing the operating cost of a wind/diesel system, it may be necessary to consider the costs associated with diesel engine starts. Each time a diesel engine is started, extra fuel is used to build up the kinetic energy of the rotating engine. Also, diesel engine wear is known to increase with each start. The resulting costs associated with these factors have been the subject of some study. Bleijs, Nightingale, & Infield (1993) concluded that the wear costs due to diesel engine starts are equivalent to about 1 to 4 minutes of full-load operating costs. In this study, this cost component is assumed to be negligible since the number of diesel starts is in the order of 1 to 2 per day.

At low output power levels, diesel engines are known to suffer from lower exhaust temperatures resulting in increased maintenance costs due to exhaust carbonization and other factors. Some diesel generator manufacturers recommend a minimum operating power of 30 or 40 percent of rated power for their generators. Below this power level, it is felt that the wear and resulting increase in maintenance costs become significant. However, there seems to be no consensus among diesel manufacturers on the significance of these effects. In this study, any increase in maintenance costs due to low power operation of the diesel generator is neglected.

3. SPECIFIC DISCHARGE STRATEGIES

3.1 System Configuration for Case Study

In this section, several possible strategies for dispatching stored wind energy are explored. A theoretical Ideal Discharge Strategy is presented as a means of evaluating the effectiveness of the practical fuzzy discharge design of the subsequent sections. Unless otherwise specified, the simulations to follow were performed assuming a hybrid power system of the following configuration:

- one 100 kW diesel generator
- three 40 kW Enertech 40/44 wind turbines
- 150 kWhr of usable battery storage
- 80% round-trip storage efficiency
- wind speed of 6.9 m/s (25 km/hr) mean
- system load of 55 kW mean
- fuel cost, $C_F = 0.26$/liter
- battery wear cost, $C_{BW} = \$0.10$/ kWhr

The characteristics of each of the major components are described in the previous chapter. The wind/load ratio for the system is 0.65 for the period under study. According to Barley's (1996) conclusions, a load-following dispatch strategy would be optimal for the system parameters specified.

The battery storage size of 150 kWhr represents about three hours of mean load capacity. Note that this is not meant to imply that this storage size is optimal for the system. Rather, the goal is to study discharge strategies for hybrids systems of any size, using the system described above as a case study. Analysis of results will determine whether conclusions can then be generalized.

3.2 Optimization Criteria

The goal of the various discharge strategies that will be presented in this study is to minimize the operating cost of the system. As has been outlined in Section 2, for the purposes of this study, the operating cost of the system is assumed to be the sum of the hourly fuel costs and battery wear costs over the entire period under study.

$$C_T = \Sigma(C_F \times F) + \Sigma(C_{BW} \times E_D) \tag{3.1}$$

where

C_T is total operating cost, \$, and

E_D is energy discharged from batteries, kWhr.

In order to assess the effectiveness of each discharge strategy presented, the total annual operating cost of each will be determined using software simulations. A dispatch time of one hour is used in all simulations.

3.3 Relative Energy Costs

When implementing a dispatch strategy in which the net system load may be met by the diesel generator, the storage batteries, or both, it is first necessary to consider the relative costs of energy from each of the sources. Using equations (2.5) and (2.6), the cost of energy per kWhr for a 100 kW diesel generator and storage batteries of various prices are plotted in Figure 3–1. Note that although a fuel cost of $0.26/liter is assumed in this illustration, it is the relative costs of diesel fuel and battery wear that are of interest.

As previously observed, the efficiency of a diesel generator increases with load. At low power levels, a diesel generator is very inefficient. Hence the per unit cost of meeting power using the generator very much depends upon the load requirement. The cost of stored wind energy, on the other hand, is approximately constant regardless of the power requirement. In deciding whether it is more favorable to meet the net load using the diesel generator or using stored wind energy, these costs must be compared.

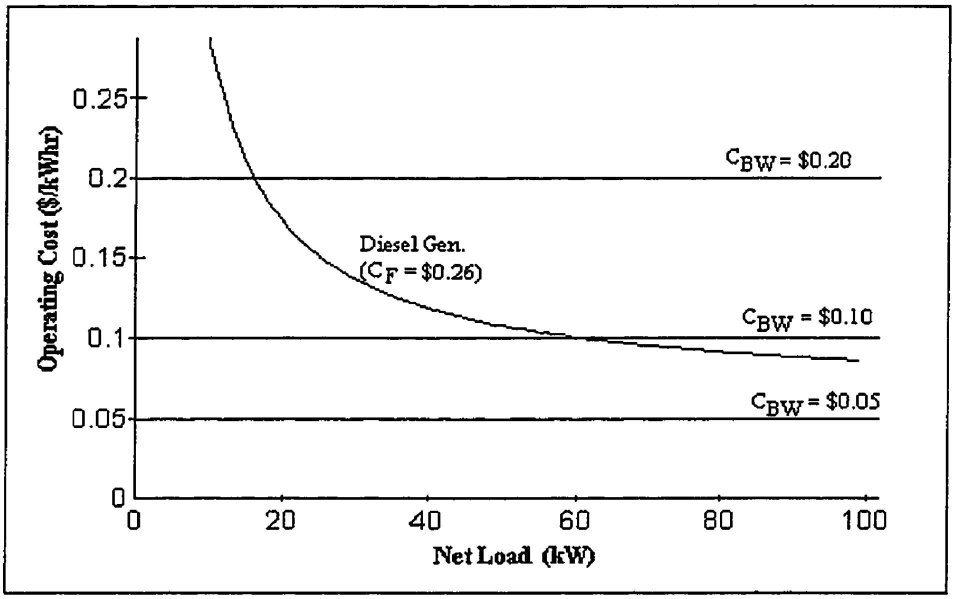

Figure 3-1 Operating costs of energy from diesel generator and from batteries

For low battery wear costs relative to fuel costs, it is always cheaper to meet the net load using stored wind energy (for example, curve C_{BW}=\$0.05/kWhr in Figure 3-1). For higher battery wear costs, it may be advantageous to use stored energy for lower net loads, and to use diesel power for high net loads (as with curve C_{BW}=\$0.10/kWhr in Figure 3-1). For very high battery wear costs, it would be economical to use stored energy for very light net loads only (as for the C_{BW}=\$0.20/kWhr curve in Figure 3-1). Thus it is important to consider the relative costs in dispatching stored wind energy. Otherwise, in some situations, it could actually be more costly to operate a system using stored wind energy than to always use the diesel generator to meet the net load requirements.

The price of diesel fuel and storage batteries vary greatly in those regions where hybrid power systems might be used. Transportation costs, tax regimes, and other factors influence the relative costs of these items. However, it can be argued that the relative price of storage batteries may be expected to decrease with improvements in technology; whereas fossil fuel costs can be expected to increase as these resources become depleted. Hence the trend may be towards systems wherein it will always be more economical to use stored wind energy than direct diesel power.

3.4 Frugal Discharge Strategy

The commonly used means of controlling battery discharge in wind/diesel systems is to use the storage batteries to meet the net load whenever the batteries have sufficient energy (see, for example, Baring-Gould, 1998). This allows the diesel generator to be shut down, reducing fuel consumption. Conventional discharge strategies mainly differ in terms of what minimum battery state-of-charge is necessary for the diesel generator to restart.

In his economic analysis, Barley (1996) suggested the use of a "Frugal Discharge Strategy" in using stored wind energy. Using this strategy, the power level below which it is more economical to use stored energy than diesel power is calculated. The dispatch controller is designed to ensure that the stored energy is used only to meet net loads below this threshold. This strategy ensures that batteries will never be used to meet loads when it would be cheaper to use diesel generator power instead.

The threshold power level for frugal discharge can be calculated by determining the point where the diesel cost curve intersects the battery cost curve of Figure 3-1. Manipulating equations (2.5) and (2.6) and solving for P yields

$$P_F = F_0/(C_{BW}/C_F - F_i) \tag{3.2}$$

where P_F is the frugal discharge threshold, in kilowatts.

For example, the Frugal Discharge Strategy for a battery cost of $0.10 and fuel cost of $.26/l would indicate that battery energy should only be used to meet net loads less than about 60 kW for a 100 kW diesel generator. Note that in cases where the cost of battery wear is less than the cost of diesel energy for all net loads, equation (3.2) gives an infinite result. In such a case the Frugal Discharge Strategy has no impact – it is always more cost effective to meet the net load using stored wind energy than direct diesel power.

3.5 Fixed Threshold Discharge

Figure 3-1 illustrates that the savings to be obtained by using stored wind energy (rather than direct diesel power) depend greatly upon the net load. This is especially true involving cases of medium battery wear costs. Consider, for example, the case of C_{BW}=\$0.10 as shown in Figure 3-2. The savings to be made by meeting a 10 kW net load are much higher than the savings at a 40 kW net load. This, of course, is because of the low efficiency of the diesel generator at low loads.

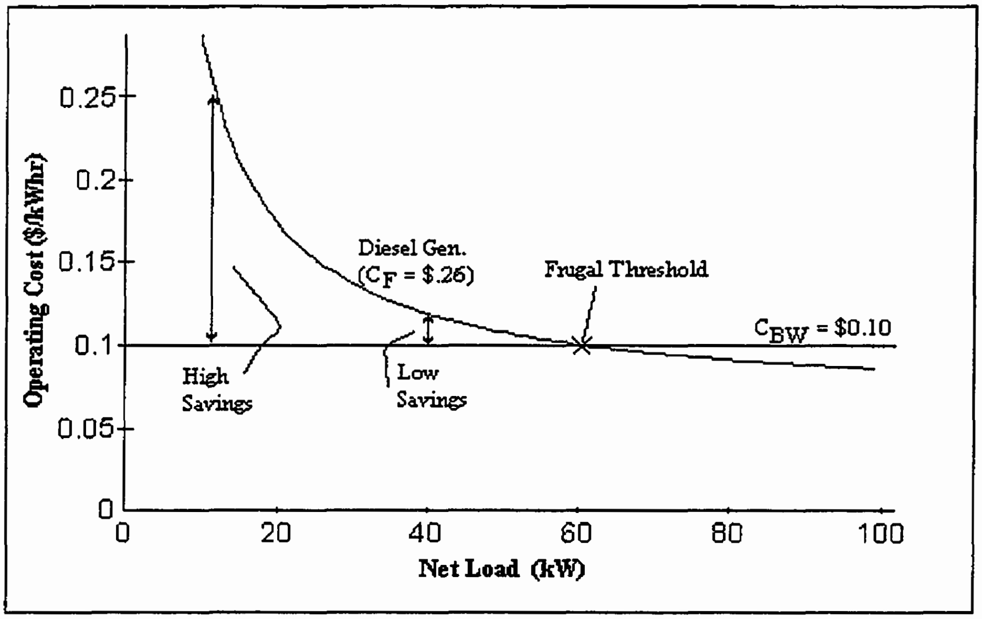

Figure 3-2 Increased savings at lower net loads

These considerations suggest that an improved discharge strategy would be to set a fixed discharge threshold at a net power level less than the frugal threshold. Below this fixed threshold, storage would be used to meet the net load if the batteries have sufficient energy. Above this threshold, diesel power would be used. By setting a low threshold, battery discharge would be limited to low net loads where cost savings are greatest.

Figure 3-3 shows how operating cost would be affected for each fixed threshold from 0 to 100 kW. This curve was produced by determining the total operating cost using a fixed-threshold discharge strategy for each threshold value from 0 to 100 kW (in 1 kW steps). A fixed threshold of 0 kW represents operating costs for no use of storage batteries at all, while a fixed threshold of 60 kW represents the operating cost of the Frugal Discharge Strategy for the system under study.

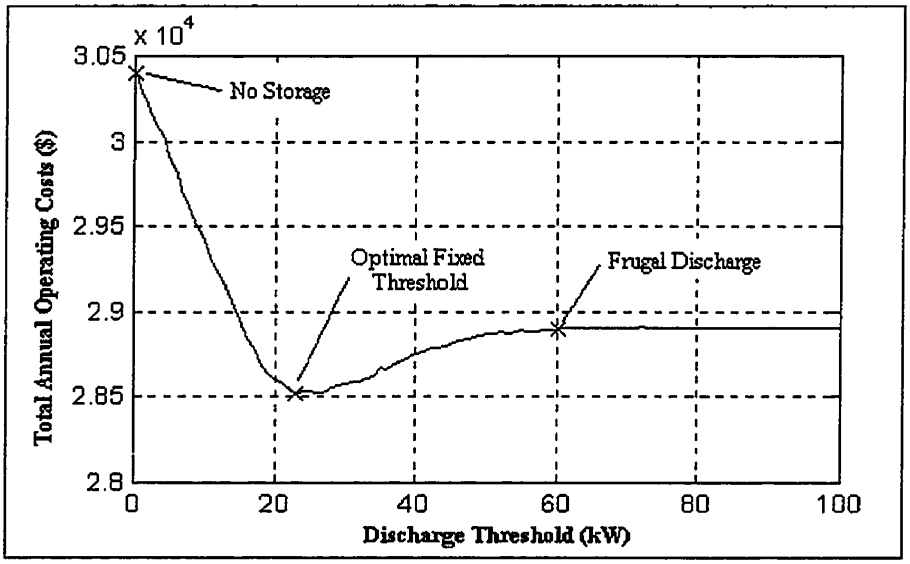

Figure 3-3 Operating costs for fixed discharge thresholds

3.6 Optimal Fixed-Threshold Discharge Strategy

The curve of Figure 3-3 shows that the optimum fixed threshold for the system is about 23 kW. At thresholds above this level, stored energy is often used to meet higher loads at the expense of future low loads where savings could be increased. At thresholds below this level, the batteries would frequently not have been completely discharged before excess wind power charges the batteries again. This means that opportunities to save costs by using the stored energy at higher power levels are missed. Nevertheless, operating at a fixed discharge threshold of about 23 kW results in a significant increase in operating cost savings relative to the frugal threshold of 60 kW.

A problem with this Optimal Fixed-Threshold Discharge Strategy is that it is impossible to know in advance the precise value of the optimal threshold. The optimal threshold depends greatly upon the wind/load ratio. The diagram of Figure 3-4 provides some insight into how the value of the optimal fixed discharge threshold is affected by the wind penetration of the system. The wind profile of the test site was scaled to simulate yearly average wind speeds from 10 to 50 km/hr. The optimal fixed discharge threshold values for various mean annual wind speeds are plotted and can be approximated by the first order equation

$$P_{OPTO} = 6.6471 + 0.7653V_{W(AVG)} \qquad (3.3)$$

where P_{OPTO} is the optimal fixed discharge threshold (in kilowatts), and $V_{W(AVG)}$ is the yearly average wind speed (in kilometers per hour).

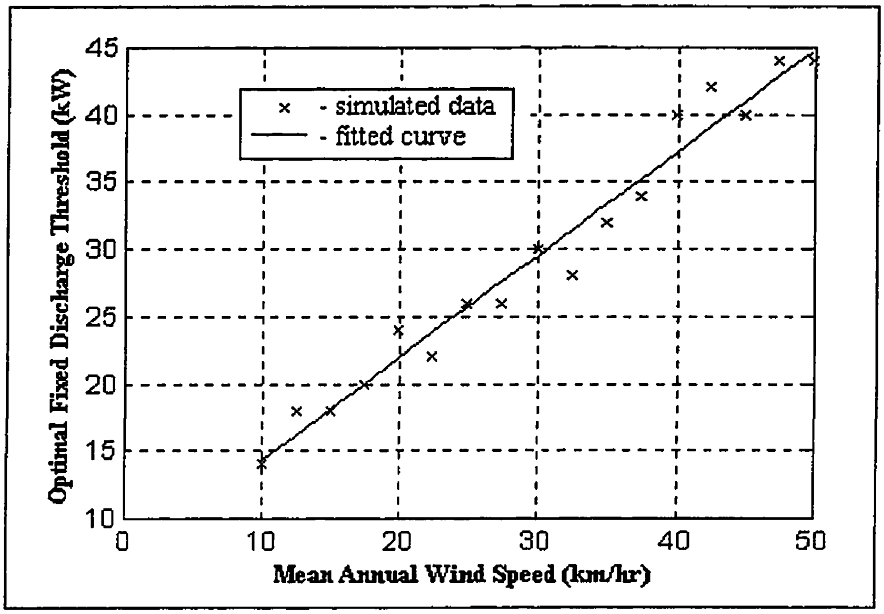

Figure 3-4 Optimal fixed discharge threshold for various mean wind speeds

Analysis of the wind data for the site under study shows that the wind/load ratio has significant seasonal variations. For a relatively windy one month period, with average wind speed of 33 km/hr, Figure 3-5 shows that the optimal fixed threshold is about 33KW, a relatively high value. This is because in such a scenario it is likely the wind will soon recharge the batteries, so it is beneficial to use the batteries to meet even relatively high loads.

For a relatively calm one-month period, with an average wind speed of 16.4 km/hr, Figure 3-6 shows that the optimal fixed threshold of about 22 kW. In this case the wind is not likely to soon recharge the batteries, so it is prudent to use the batteries to meet only relatively low loads.

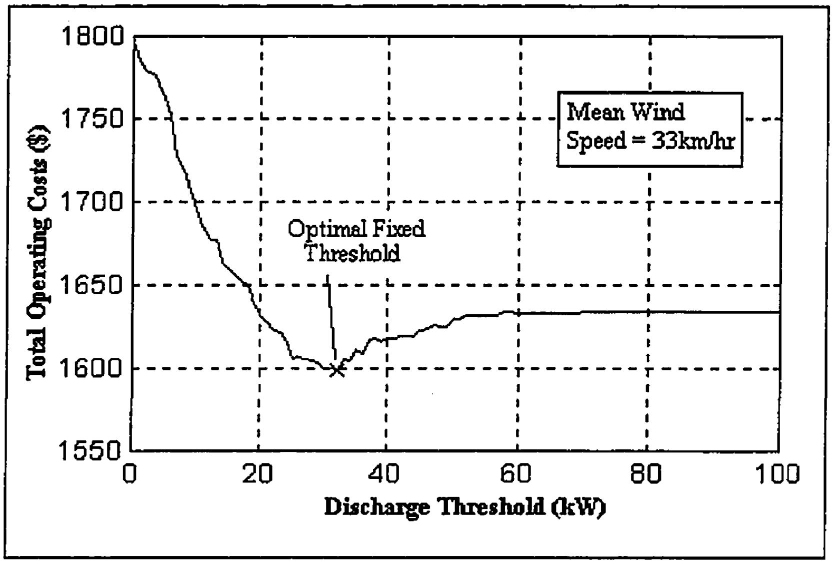

Figure 3-5 Fixed set-point strategies for a month of high winds

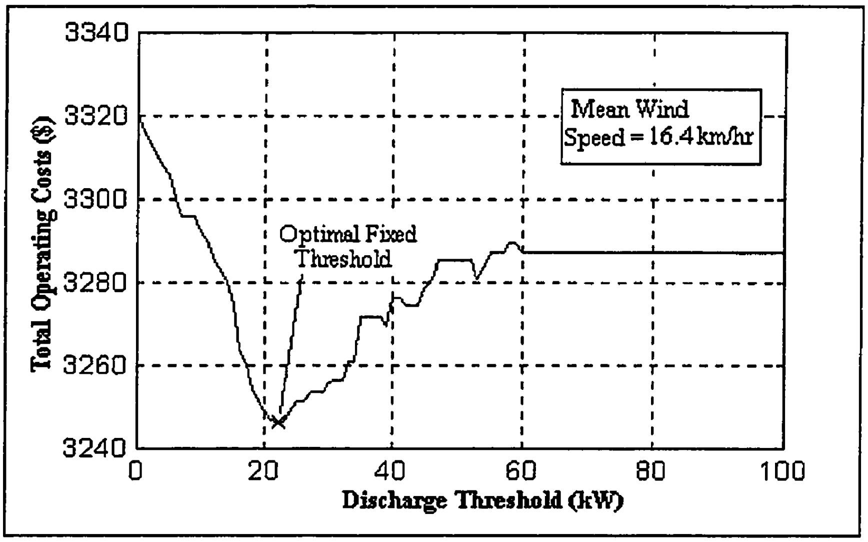

Figure 3-6 Fixed set-point strategy for a month of low winds

Over time, the wind/load ratio changes due to seasonal wind patterns and weather systems. Hence, any particular fixed discharge threshold will not be optimal in all situations. It would seem that better performance could be attained if the discharge threshold varied depending upon the wind conditions, so that the controller would automatically adjust to an optimal discharge threshold. This approach will later be used in the design of a fuzzy discharge controller.

3.7 Ideal Discharge Strategy

An ideal discharge strategy would be one that makes use of stored wind energy by always using this energy to meet those net loads that will result in maximum cost savings over the entire period. A theoretical Ideal Discharge Strategy can be simulated if exact load and wind conditions for the entire period under study are known. The proposed ideal strategy is, of course, not achievable in practice since perfect knowledge of future wind and load conditions is impossible in the real world. However, the resulting savings can be used as a benchmark in evaluating more practical discharge strategies. (Figure 3-7 shows the cost reduction that would be attained if it were possible to operate the system using this ideal strategy.) The algorithm of the Ideal Discharge Strategy is outlined in the steps below:

1. Find the lowest positive net load in the entire period under study.
2. If this net load is less than the frugal threshold and the storage contains sufficient energy to meet this net load, assume it will be met by storage. Otherwise, use the diesel to meet this net load.

3. Check whether meeting this net load with storage will preclude use of storage to meet one of the previous discharges. If it will, then meet this net load using the diesel. Otherwise, use storage to meet this net load.
4. Repeat steps 2 & 3 for the next lowest positive net load until all net loads have been considered.

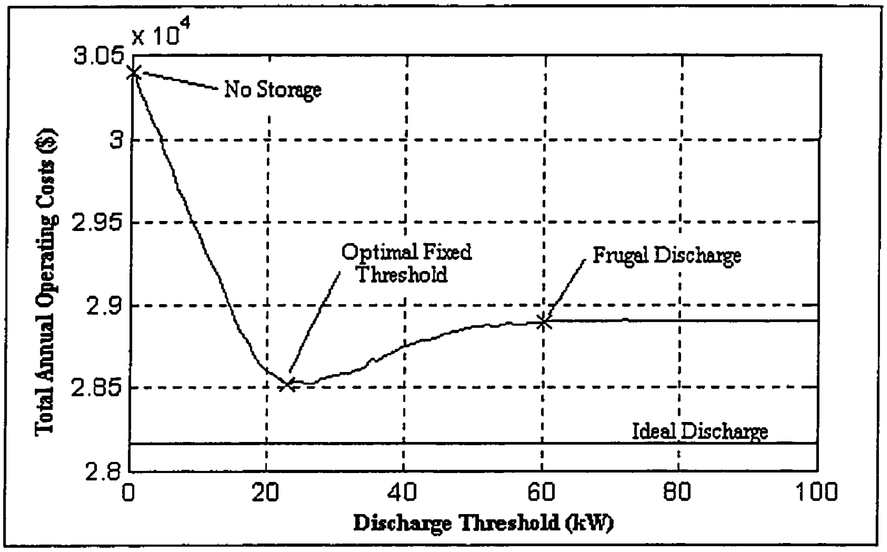

Figure 3-7 Cost reduction using the Ideal Discharge Strategy

Using the Ideal Discharge Strategy will result in operating cost savings no matter what the wind/load ratio and relative battery price. Figure 3-8 shows simulated results over a range of wind/load ratios for battery wear costs of $0.10/kWhr. In deriving these curves, the wind/load ratio was varied by assuming the number of wind turbines as being a continuous rather than a discrete variable. The number of turbines was adjusted to simulate a range of W/L ratios. The curves represent percentage saving in annual operating costs using the Frugal Discharge Strategy and using the Ideal Discharge Strategy relative to costs using no storage. A storage size of 150 kWhr is assumed.

These curves show that savings can be significantly increased compared to the Frugal Dispatch Strategy. At a W/L ratio of 1.0, for example, frugal discharge of the storage batteries results in a total operating cost reduction of about 7.5% relative to no use of storage. Ideal discharge, on the other hand, reduces operating costs by about 10.5%. Thus the savings achieved by introducing long-term storage into the system can be increased by 40% with the Ideal Discharge Strategy. Clearly, such an increase in savings could have significant impact on the economic viability of long-term storage.

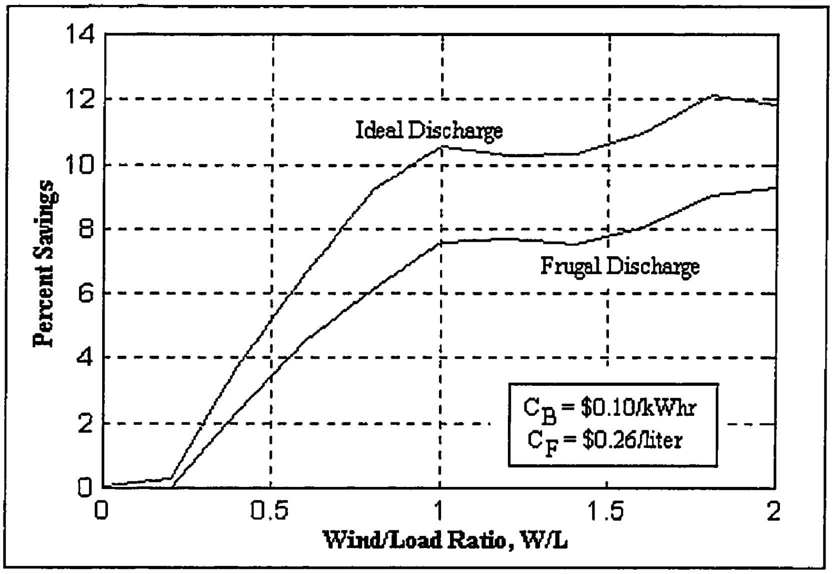

Figure 3-8 Potential increase in savings for C_{BW} = $0.10/kWhr

Similar improvements in savings can be attained for other relative battery wear costs. Figure 3-9 shows the amount savings would be increased for a 150 kWhr capacity using the Ideal Discharge Strategy relative to using frugal discharge for a variety of battery wear costs and WLR values. As the figure shows, savings can always be increased using the Ideal Discharge Strategy, though maximum improvements are obtained for systems with a low WLR. At high wind penetrations, it is likely that the storage batteries will soon be recharged, and the intelligent allocation of stored wind energy is not so critical to operating costs. As wind penetration decreases, the method of dispatching stored wind energy has a more significant impact.

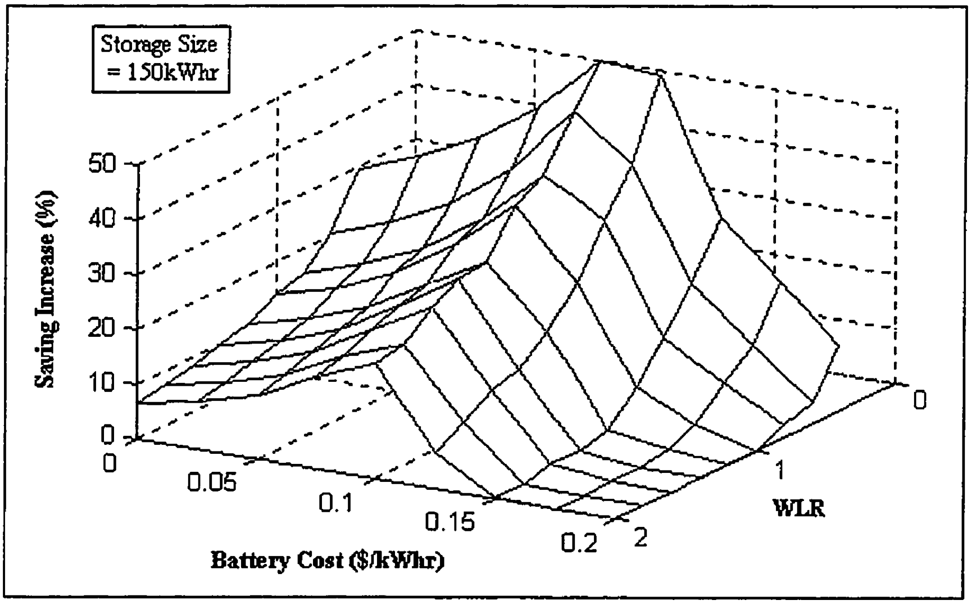

Figure 3-9 Potential increase in savings using Ideal Discharge Strategy

At high battery costs, the frugal threshold is quite low and the batteries would be used so rarely that little savings can be achieved regardless of the dispatch strategy. At very low battery prices, the cost of using battery energy is always much less than the cost of diesel power and the discharge strategy has little effect. In such a case, a larger storage size might well be justified.

This discussion described how optimal use of stored wind energy can result in a significant increase in the savings made possible by the use of long-term storage in a wind/diesel system. Though the ideal strategy is entirely academic in nature, it does provide an incentive to implement a practical discharge controller that can come close to achieving similar performance. That task is the focus of the remaining sections of this report.

4. A FUZZY DISCHARGE STRATEGY

An improved discharge strategy based on the use of fuzzy logic is now presented. The goal is to design a practical discharge controller that can perform better in terms of reducing operating costs than the practical discharge strategies discussed previously. The philosophy of the fuzzy control strategy is presented in this chapter, followed by details of its implementation in the next.

4.1 Fuzzy Control Strategy

There are two factors that need to be considered in implementing an improved discharge strategy: the current state of charge of the storage batteries and a forecast of future wind conditions.

4.1.1 Current Battery State of Charge (SOC)

As has been shown in the previous chapter, for net loads less than the frugal threshold, it is advantageous to use stored wind energy rather than direct diesel power. However, with limited storage capacity, which nets loads should be met by storage depends upon the amount of energy contained in the batteries.

For example, consider the net load profile of Figure 4-1a. Both sections of this load are less than the frugal discharge threshold of 60 kW, so meeting these loads using stored energy will result in savings. If the amount of stored energy is sufficient, then the batteries should be used to meet the entire load as shown in Figure 4-1b. However, if the stored energy is not sufficient to meet the entire load, then only the lower load should be met by storage. Meeting the higher load with stored energy will deplete the storage making it impossible to take advantage of the greater savings possible in meeting the lower load. As Figures 4-1c & d show, when the state of charge (SOC) is low, greater savings occur if discharge is delayed until the net load drops to the lower level.

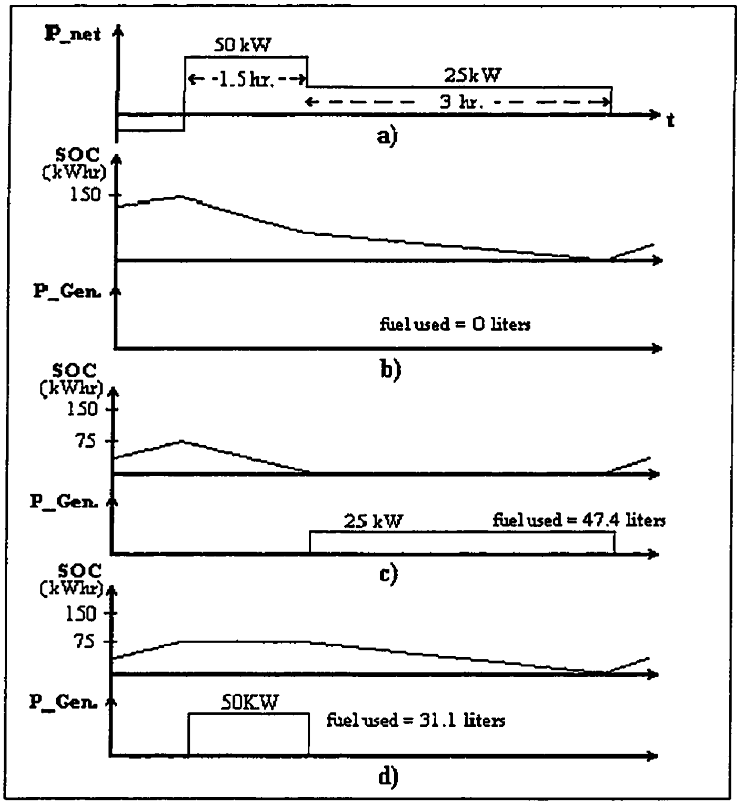

Figure 4-1 Effect of battery SOC on discharge strategy

In general, the effect of state of charge may be summarized by observing that if the SOC of the batteries is high, then high net loads should be met using stored energy.

However as the SOC decreases, the stored energy should be used more conservatively, reserving it for lower net loads where cost savings will be maximized.

4.1.2 Forecast of Future Wind Conditions

In addition to the battery SOC, the future wind conditions also play a role in optimizing the dispatch of stored wind energy. Consider the net load profile of Figure 4-2a. Again, both positive sections of this load are less than the frugal discharge threshold, thus savings can be made by meeting these loads using stored energy. However, since the storage has limited capacity, the amount of savings realized depends upon how the stored energy is dispatched.

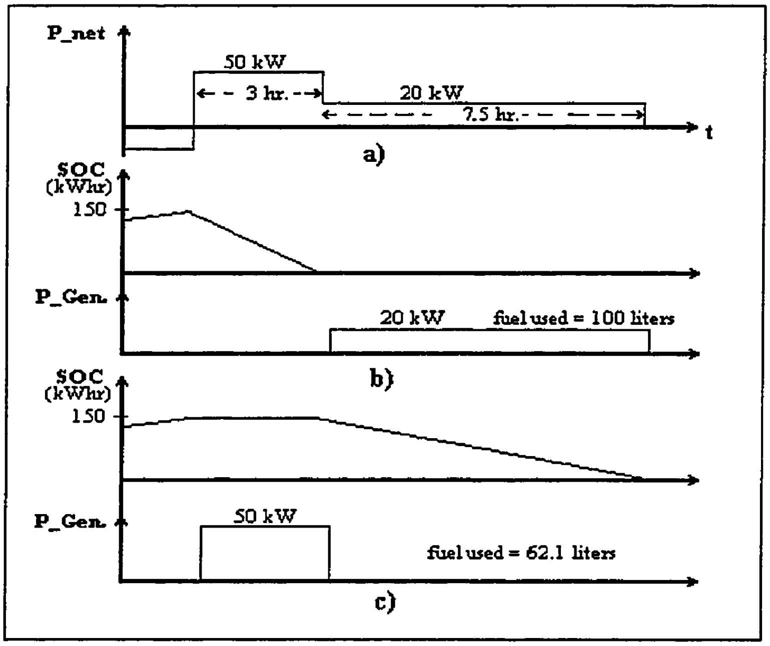

Figure 4-2 Effect of future net load on dispatch strategy

If discharge is delayed until the net load drops to the lower value, fuel savings will be increased compared to meeting the higher load with stored energy. These two options are illustrated in Figures 4-2 b & c. In both cases, the cost in terms of battery wear is the same since both use 150 kWhr of stored energy.

In order to implement such a discharge strategy, it is necessary to be able to predict the future value of net load. Figure 4-3 illustrates what can happen if the prediction is wrong. Here discharge of the batteries is delayed in the expectation that the net load will decrease, making discharge more advantageous later. Instead however, the net load becomes negative providing an opportunity to charge the batteries. Since the batteries had not yet been discharged, excess wind energy is spilled. In this situation, it would have been better to use the stored energy to meet the 50 kW load and thus be able to store the new excess wind energy.

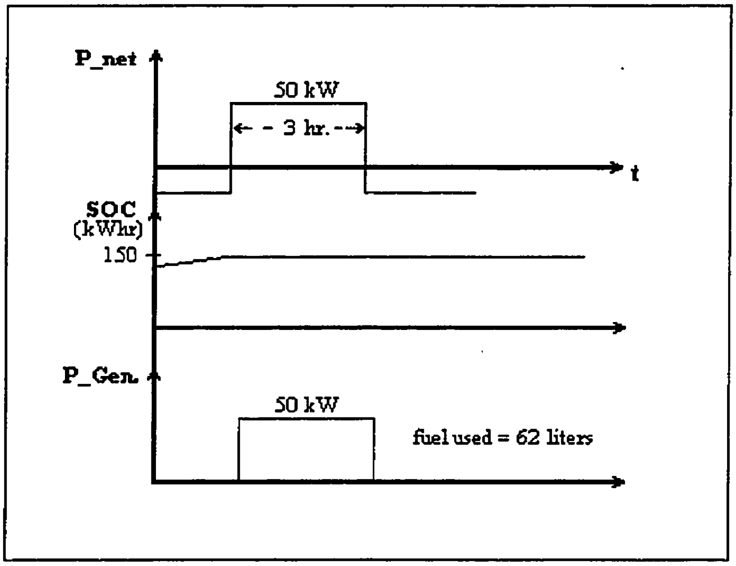

Figure 4-3 Delaying discharge results in lost opportunity to save

Hence a predictive discharge strategy is risky – it can result in increased fuel savings if it is able to make accurate predictions, but it can result in increased costs (lost opportunities to store excess wind energy) if predictions are wrong.

Variations in net load depend upon both wind-generated power and system load. However, variations in wind power are much higher than load variations in the system under study. (Annually, system load has a mean of 55 kW with a standard deviation of 12.6 kW, whereas system wind power has a mean of 35.1 kW with a standard deviation of 37 kW.) Thus, a forecast of wind speed can give a more accurate indication of future net load than can a load forecast.

Using predicted wind speed as an indication of future net load, it can be concluded that if the wind is not expected to be high in the near future, then the batteries should be used to meet only relatively low net loads. However if the wind is expected to be high, then storage should be used more liberally as the batteries will soon be recharged. If the predictions of future wind conditions are accurate, then this strategy should reduce operating costs.

Although it is unrealistic to expect to predict future wind conditions exactly, it should be possible to obtain a reasonably accurate prediction. After all, meteorologists routinely forecast average wind conditions for periods up 5 days based upon prevailing weather systems.

4.2 Controller Structure

The previous sections outlined two factors that can be considered in devising an improved controller:

1. Battery SOC. It was shown that, in general, as the SOC of the batteries decreases, so too should the threshold of net loads to be met by storage.
2. Future wind speed. If the wind is expected to be high soon, the batteries should be used to meet higher loads, whereas if no high winds are expected, then the batteries should only be used to meet low net loads.

This suggests that a controller could be designed that varies the discharge threshold based upon these two factors. This controller will have two inputs (current SOC of the storage batteries, and a forecast of wind conditions) and one output (net power threshold for battery discharge). The discharge threshold will be used by the system dispatch controller in determining whether to meet the net load by using stored wind energy or by using direct diesel power.

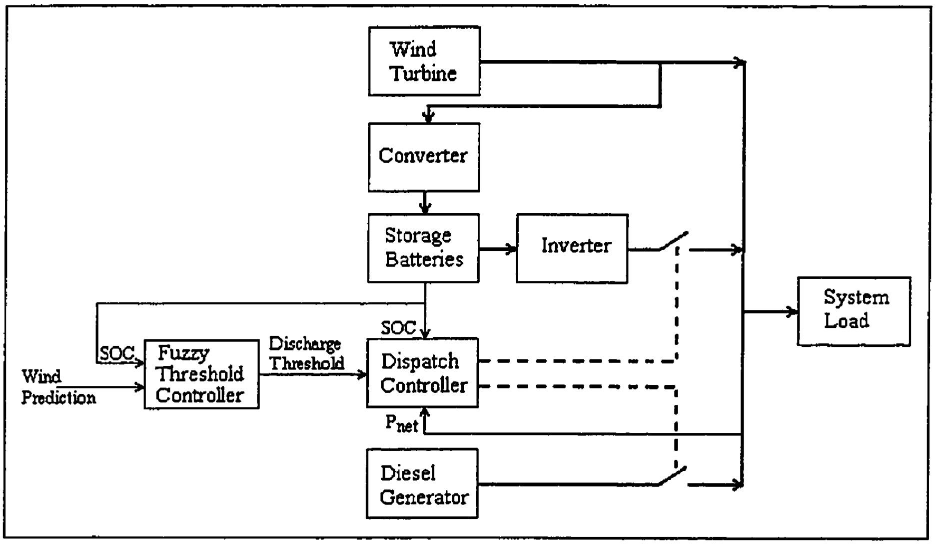

Figure 4-4 Block diagram of fuzzy discharge control

Figure 4-4 shows how the discharge threshold controller would be incorporated in the system dispatch scheme. The dispatch controller monitors system net load and battery SOC. If the average system net load is below the discharge threshold and if the storage batteries contain sufficient energy, then the diesel generator is turned off and the batteries used to meet the net load. The role of the fuzzy threshold controller is to adjust continuously the discharge threshold for optimal performance based on battery SOC and expected wind conditions.

4.3 The Choice of Fuzzy Logic

In order to implement the controller, fuzzy logic is used. Fuzzy logic is well suited to the task for a number of reasons. Primarily, an exact mathematical model defining how the two input variables (battery SOC and future wind conditions) should best be used to influence the value of output (the discharge threshold) is not known. Instead, we have the rather vague reasoning of how an improved strategy might be achieved as outlined above. Thus a design that implements this type of approximate reasoning is needed.

Fuzzy logic is a linguistic approach to problem solving first proposed by Zadeh in the mid-1960s (Ross, 1995). Fuzzy logic has since found application in the field of control systems as the basis for the fuzzy logic controller (FLC). An FLC is a type of expert controller that has been widely used in applying the often incomplete knowledge of human experts to systems that lack a rigorous mathematical model. FLCs have been used successfully in a large number of control applications (Lee, 1990).

Secondly, there is inherent inaccuracy in any prediction of future wind conditions. FLCs are known to be very useful in systems with such inaccuracies (Lee, 1990). Finally, wind forecasts are frequently made using linguistic terms (very windy, low winds, etc.). Fuzzy logic can easily incorporate such linguistic terms in implementing fuzzy rules and fuzzy membership sets.

5. FUZZY CONTROLLER IMPLEMENTATION

The basic configuration of a fuzzy logic system is illustrated in Figure 5-1 (Wang, 1994, p. 6). A fuzzy system is a means of mapping a set of input variables x in a universe of discourse U to a set of outputs y in a universe of discourse V. The function of each component of this system is now examined and its application to the design problem described.

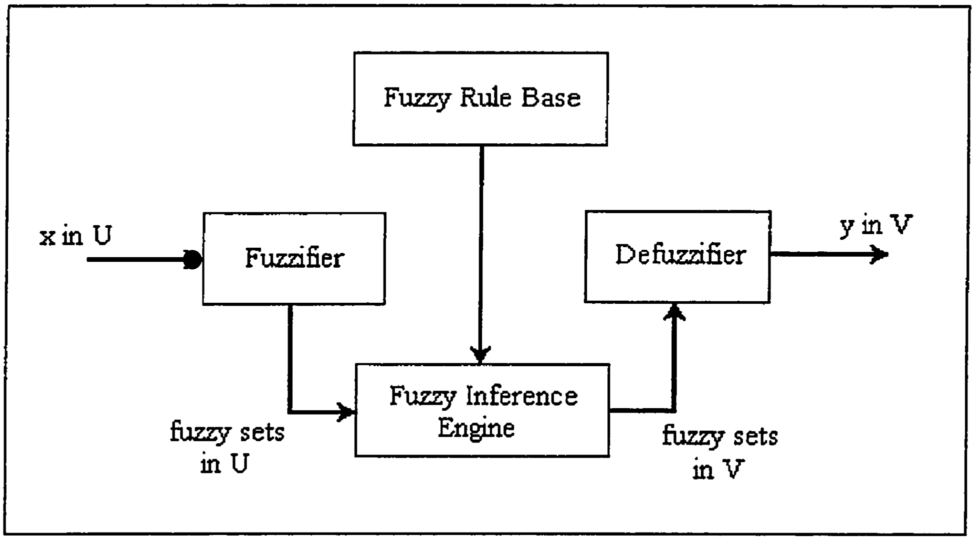

Figure 5-1 Basic configuration of a fuzzy system

5.1 Fuzzy Sets and Membership Functions

Conventional control methods describe input and output variables using what are known as "crisp" values. A crisp value is a specific numeric value used to describe the state of a variable. In this design problem, the input variable SOC is a measure of usable energy currently stored in the batteries. This is represented as a percentage of total battery capacity. In crisp terms, the current battery SOC might be described as being 75%, for example.

In fuzzy systems, on the other hand, variables are described in terms of their degrees of membership in particular fuzzy sets (also known as memberships functions). These fuzzy sets are usually referred to in linguistic terms. In this implementation current battery SOC is defined in terms of the three fuzzy sets: Low, Medium, and High. The definition of what range of SOC constitutes each of these fuzzy sets is illustrated in Figure 5-2. Similarly, fuzzy sets are assigned to the other system variables - predicted wind speed, and output discharge threshold. These membership sets are illustrated in Figures 5-3 and 5-4.

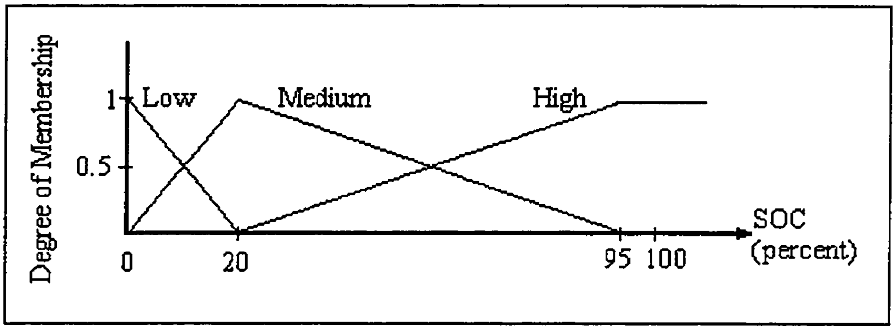

Figure 5-2 Membership functions for battery SOC input variable

The predicted wind speed variable is a measure of maximum hourly average wind speed expected within the next 12 hours. This is represented in kilometers per hour since meteorological forecasts are likely to use these units. It was found through simulations that a forecast period of 12 hours resulted in optimal performance. Practical considerations of providing such forecast information to the controller will be addressed in a later section.

The output of the fuzzy controller is the discharge threshold, in kW. This output variable is used by the dispatch controller. If the net load is below the discharge threshold and the storage batteries have sufficient energy, then the net load will be met by the storage batteries alone, allowing the diesel generator to be turned off. Otherwise, the diesel generator alone will be used to meet the net load.

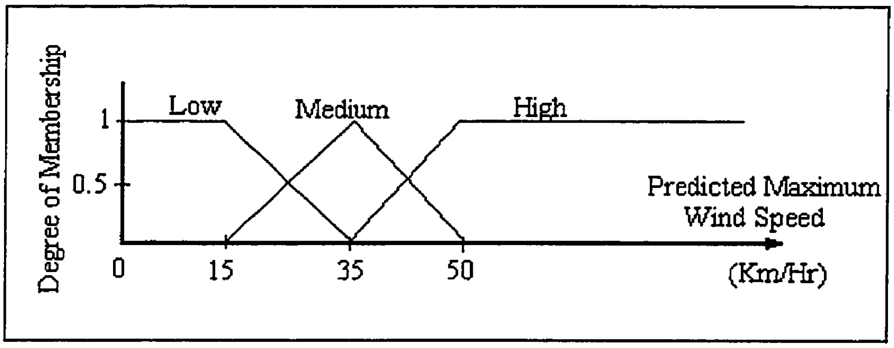

Figure 5-3 Membership functions for wind prediction input variable

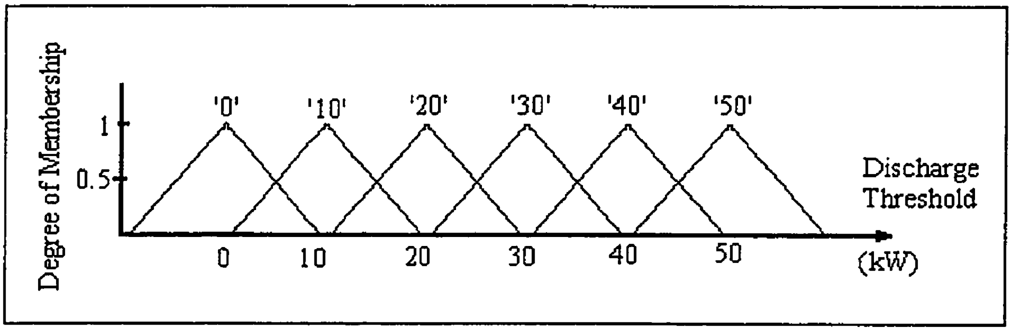

Figure 5-4 Membership functions for discharge threshold output variable

There are a number of shapes that could be used to define the membership functions in a fuzzy system. Triangular, trapezoidal, Gaussian, and sigma functions are among those that have been used in various applications. Each of these has its own advantages and characteristics. Triangular membership functions are used in this design as these are the most straightforward to describe and simple to implement mathematically. Other shapes were experimented with in the design process, with no significant improvement in overall system performance.

The precise limits of each fuzzy set, as well as the number of membership functions for each controller variable, were adjusted through a process of simulation trial and error in order to give satisfactory system performance. The number of memberships for each variable was kept as low as possible without significantly hindering controller performance. This was done in order to avoid the "rule explosion" that results from a high number of memberships functions (Kosko, 1997).

5.2 Fuzzification

Since the input variable SOC would be measured as a crisp value, it must be converted to a fuzzy value for use in a fuzzy system. The process of converting crisp inputs from the real world to fuzzy variables for use in the fuzzy system is known as "fuzzification." The degree to which an input variable belongs to any fuzzy set is referred to as the degree of membership, $\mu(x)$. For example, as illustrated in Figure 5-5, a SOC input with a crisp value of 75%, has degrees of memberships $\mu_{Low}(75)=0$, $\mu_{Medium}(75)= 0.27$, and $\mu_{High}(75)= 0.73$.

The degree of membership is also referred to as the "truth" value. Using this terminology, the battery SOC could be described as having a truth of 0.27 for the Medium membership function, for example.

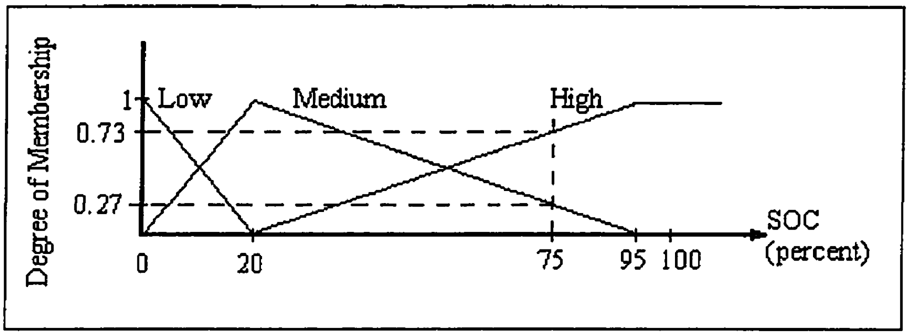

Figure 5-5 Fuzzification of crisp input battery SOC = 75%

5.3 Fuzzy Rule Base

The next step in the fuzzy controller design is to describe the fuzzy rules that embody the expert knowledge of how the controller should operate. These rules are of the form

IF X1 is A AND X2 is B THEN Y1 is C.

Each fuzzy rule is made up of two parts known as the antecedent and the consequent. The antecedent is the IF part of the fuzzy rule. The degree to which this part is true determines the degree to which the corresponding THEN part (the consequent) is used in determining the output variable. It is the role of the fuzzy inference engine to perform this evaluation. An example rule for this application is

IF SOC is *High* AND V_P is *High* THEN Discharge Threshold is '50' where V_P is the predicted maximum hourly wind speed (in kilometers per hour).

For the membership sets used in this application, a total of nine fuzzy rules are necessary. These can be summarized in the form of a fuzzy associative memory (FAM) as shown in Figure 5-6. These rules are based on the intuitive reasoning described earlier, and were optimized using trail and error computer simulations.

Wind \ SOC	Low	Med	High
Low	0	10	20
Med	0	10	30
High	20	30	50

Figure 5-6 Fuzzy associative memory (FAM)

5.4 Fuzzy Inference Engine

The fuzzy inference engine applies the fuzzy rule base to the fuzzified input variables in order to determine a corresponding output. In order to do this the inference engine must first evaluate the antecedent of each rule to determine it truth. As the fuzzy system under consideration has two input variables, each antecedent has the form

$$\text{SOC is A AND } V_P \text{ is B}$$

As was previously discussed, the truth of each part of the antecedent is determined by the crisp input values and the corresponding input membership functions. Several methods may be used to determine the overall truth of the antecedent. Of these, the most commonly suggested are the min method and the product method. The product method, which is used in this implementation, calculates the truth as

$$\mu(X) = \mu_A(X1) \times \mu_B(X2). \tag{5.1}$$

Thus, for example, if $\mu_A(X1)$ is 0.5 and $\mu_B(X2)$ is 0.9, then $\mu(X)$ is 0.45 .

The manner in which the truth of the antecedent of the rule affects the rule consequent is often referred to as the implication method. Again, there are a variety of implication methods used in practice. The one used in this design is known as the product implication method. This method scales the output membership function C by the truth $\mu(X)$ of the IF part of the rule. This is best illustrated using a graphical example.

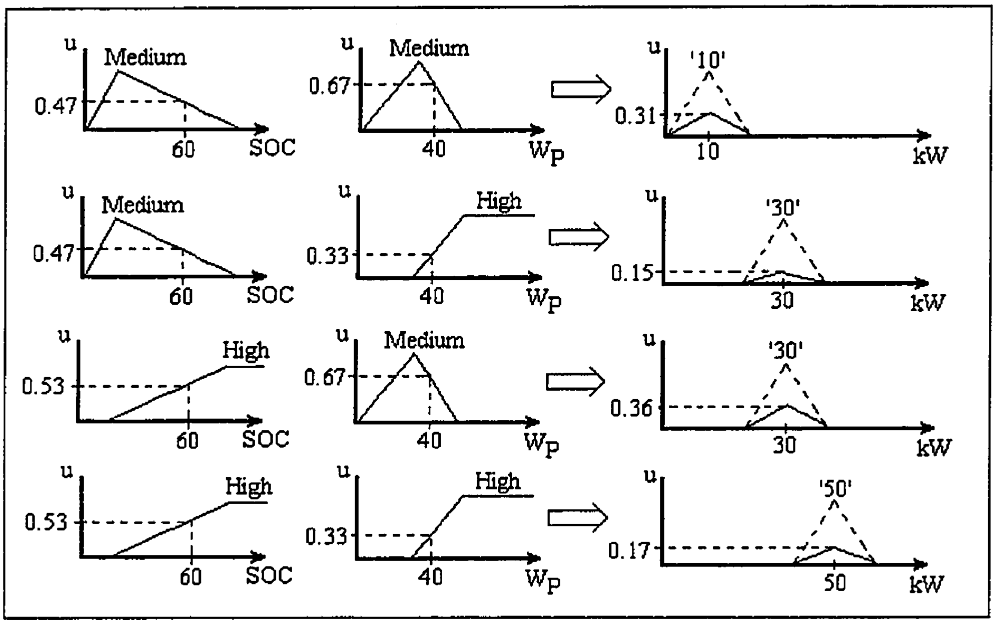

Figure 5-7 Example of fuzzy inference engine rule evaluation

Consider the case for a current battery SOC of 60% and a predicted maximum wind speed of 40 km/hr. For these input values, the fuzzifier, together with the fuzzy inference engine, evaluates the effect of each of the nine fuzzy rules in the rule base on the output variable. Due to the number and shape of input membership functions used in this system, only four of the nine rules will have non-zero truths for the antecedent. These four rules are said to "fire." The effects of each of these rules on the output membership functions are illustrated in Figure 5-7.

The final task of the fuzzy inference engine is to combine the consequent of each of the fired rules. As in other aspects of the design, there are a variety of methods that can be used in forming this combination. For this implementation, the summation combiner method was selected. This means that all of the scaled output membership functions resulting from the evaluation of the fuzzy rule base are added together to form the fuzzy output Y. For the rule consequent of Figure 5-7, the corresponding output fuzzy variable would be that shown in Figure 5-8.

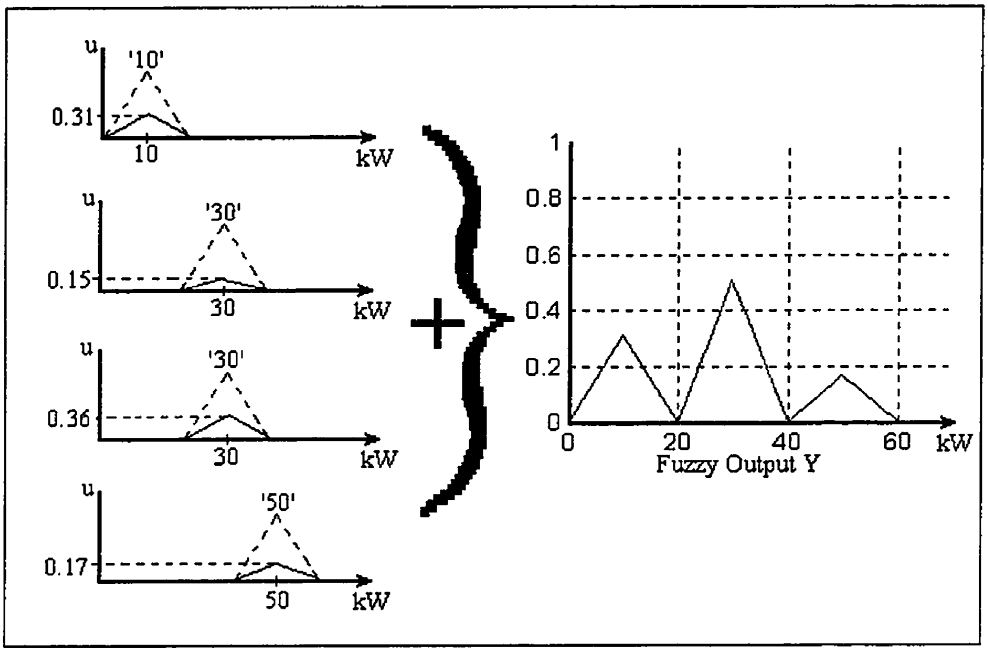

Figure 5-8 Summation combiner used to determine fuzzy output

5.5 Defuzzification

The fuzzy inference engine determines the fuzzy output variable Y based upon the methods discussed. This variable, however, must be converted to a crisp value for use as a final output. In this system, the crisp output is the discharge threshold to be used by the power system dispatch controller. The process of converting a fuzzy output variable to a crisp value is known as "defuzzification."

There are a few different defuzzification methods commonly in use. The centroid method seems to be by far the most popular and is used in this design. Using centroid defuzzification (also known as the center of gravity method) the area under the output fuzzy variable is treated as a surface area. The horizontal center of gravity of this area is calculated and is used as the corresponding crisp output. Thus, for the fuzzy output Y of Figure 5-8, the corresponding crisp output is determined to be 27.3 kW as illustrated in Figure 5-9.

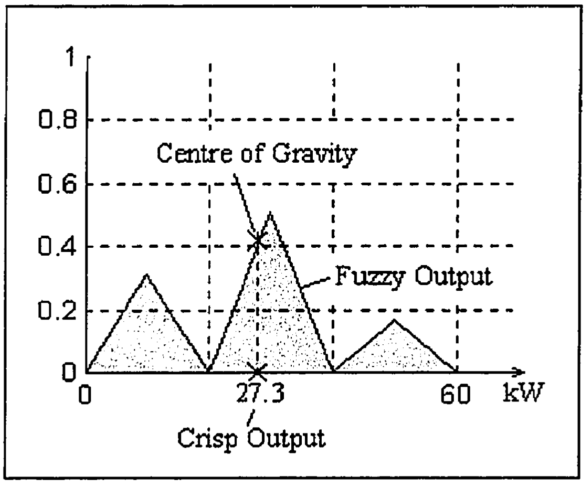

Figure 5-9 Defuzzification yielding a crisp output value

5.6 Fuzzy Control Surface

The fuzzy controller performs a mapping of current battery SOC and predicted maximum wind conditions to the system battery discharge threshold. This mapping can be visualized as the control surface of Figure 5-10.

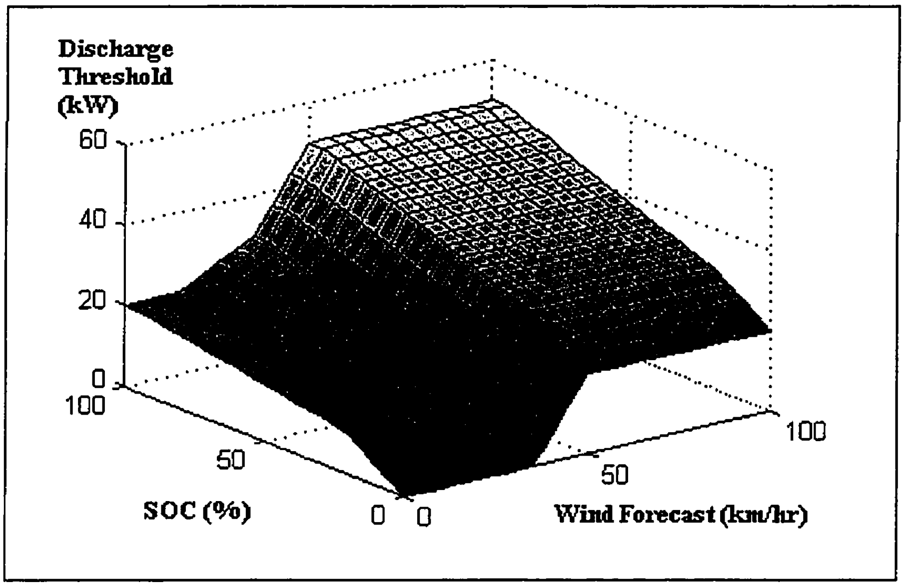

Figure 5-10 Control surface for fuzzy discharge threshold controller

5.7 Fuzzy System Design Considerations

As apparent from the previous discussion, several design choices were made in implementing the fuzzy controller. The product method of rule implication and the summation combiner method are examples of such choices. The implementation of the fuzzy design presented here conforms to a format referred to by Kosko (1997) as the "standard additive model (SAM)." One advantage of the SAM over other possible implementations is that it uses only the standard arithmetic operations of addition, subtraction, multiplication and division. This can make it easier to implement in digital hardware devices and can also result in decreased execution time.

Several other design choices were tested in designing the fuzzy inference engine. For example the "min method" of rule implication was tried in place of the product method. However, the overall performance of the controller was not significantly affected by any of these variations. Hence the SAM model was chosen for final implementation.

6. RESULTS

In this chapter, the performance of the Fuzzy Discharge Controller is examined by comparing simulated performance of the system using the following discharge strategies:

1. No use of storage
2. Frugal Discharge Strategy
3. Optimal Fixed-Threshold Discharge Strategy
4. Fuzzy Discharge Controller
5. Ideal Discharge Strategy

Various aspects of system performance are presented and discussed.

6.1 Summary of Results

Table 1 displays the operational characteristics of the system over a one-year simulation period. For each discharge strategy, total operating costs, total fuel costs, total battery usage, number of diesel starts, total diesel running time, and expected battery lifetime are listed. Figures 6-1 to 6-4 graphically illustrate several of these operational characteristics.

Table 1 – Performance Results

Discharge Strategy	Total Operating Costs ($)	Fuel Costs ($)	Battery Usage (kWhr)	Diesel Starts	Diesel On Time (hrs)	Batt. Life (yrs)
No Storage	30424	30424	NA	413	6519	NA
Frugal Discharge	28897	26965	19321	358	5503	6.2
Optimal Threshold	28517	27252	12645	535	5439	9.5
Fuzzy Discharge	28353	26730	16226	532	5305	7.4
Ideal Discharge	28169	26315	18547	528	5183	6.5

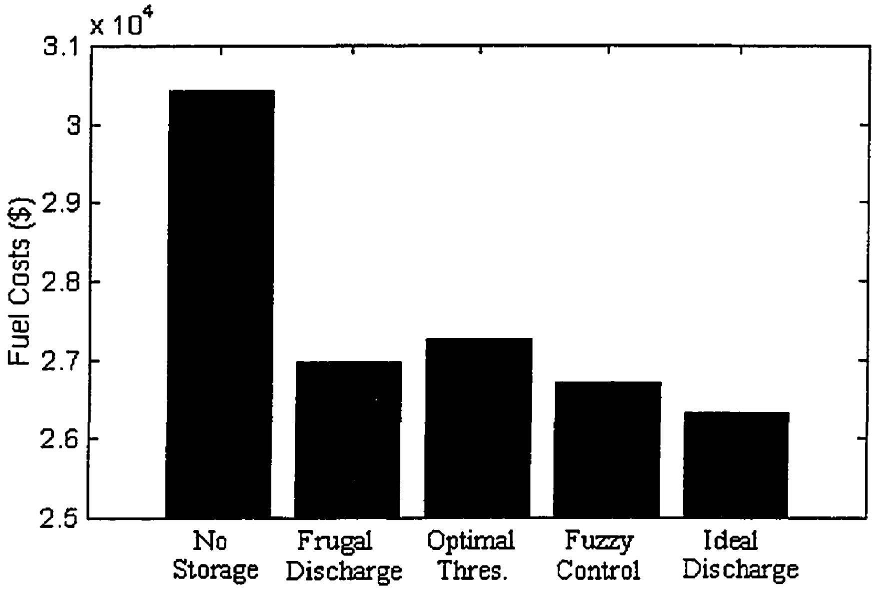

Figure 6-1 Annual fuel costs

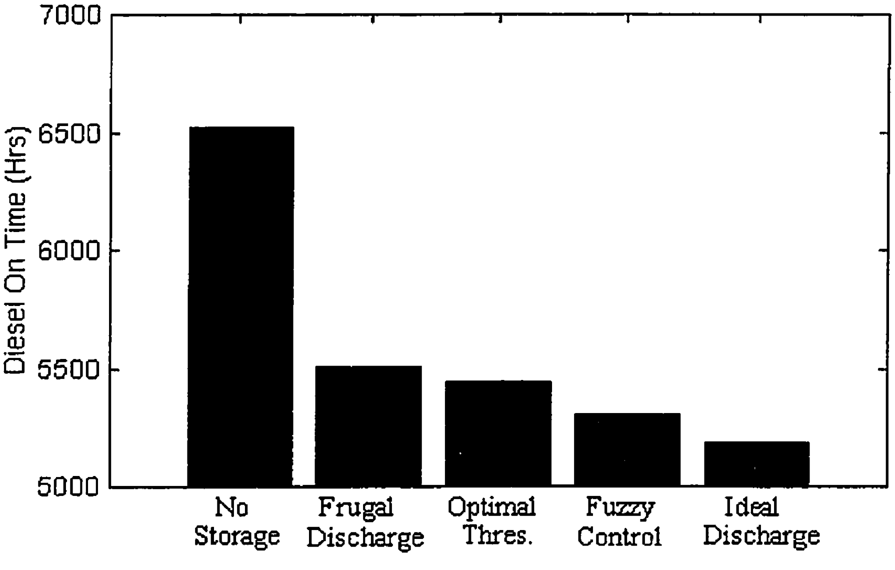

Figure 6-2 Diesel generator annual running time

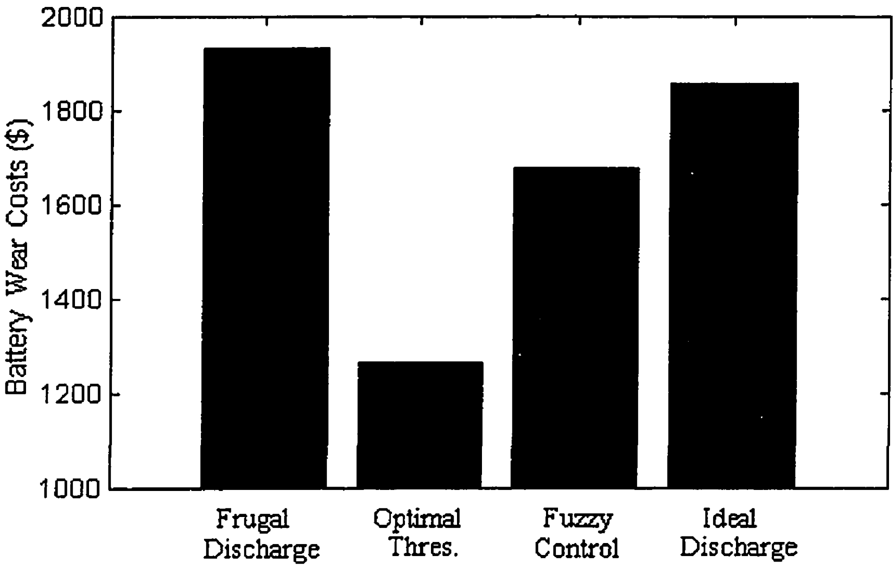

Figure 6-3 Annual battery wear costs

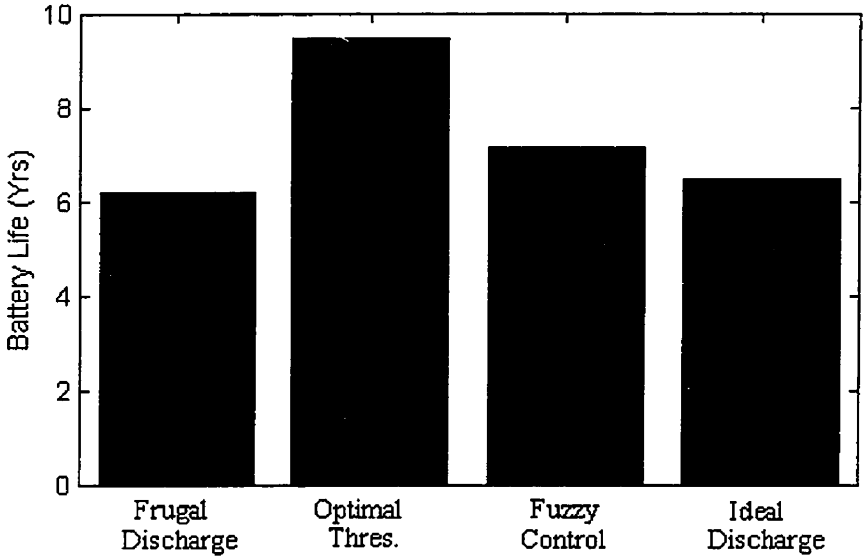

Figure 6-4 Expected battery lifetime

6.2 Analysis of Results

6.2.1 Total Operating Costs

The total annual operating costs for the system are illustrated graphically in Figure 6-5. As the figure shows, the Fuzzy Discharge Controller reduces operating costs relative to all other practical discharge strategies, though of course not as much as the Ideal Discharge Strategy.

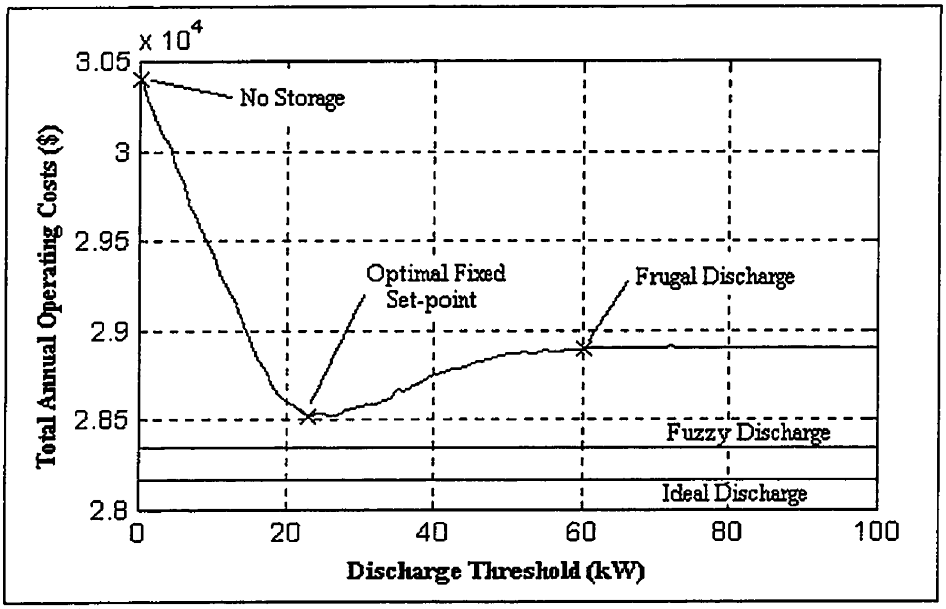

Figure 6-5 Total annual operating costs

In these simulations, the fuzzy controller was continuously provided with perfect forecasts of wind conditions for a forecast time of 12 hours. The possible sources for such forecast information and the effect of errors in the forecast will be discussed shortly.

For purposes of comparing performance, it is useful to examine the relative amount of savings obtained using each discharge strategy. One way to do this is to calculate the savings for each discharge strategy relative to the operating costs for no use of long-term storage . The savings are summarized in Table 2.

Table 2 – Relative Reduction in Operating Costs

Discharge Strategy	Operating Cost Reduction (%)
Frugal Discharge	5.02
Optimal Fixed-Threshold	6.27
Fuzzy Controller	6.81
Ideal Discharge	7.41

6.2.2 Frugal Discharge Strategy

The Frugal Discharge Strategy makes maximum use of stored wind energy since the batteries may be used to meet the load whenever the net load is less than the frugal discharge threshold. As a result, the battery wear costs for this strategy are greater than any other strategy. Fuel consumption is reduced compared to no storage; however, the total operating costs are not minimized because stored energy is not dispatched in an optimal manner.

6.2.3 Optimal Fixed-Threshold Discharge Strategy

The Optimal Fixed-Threshold Discharge Strategy is very conservative in terms of dispatching stored wind energy. Storage batteries are only used to meet net loads less than the relatively low threshold of 23 kW. Thus there are often situations where the storage batteries have not been completely discharged before excess wind energy again becomes available to charge the batteries. The result is an increase in spilled wind energy. As a consequence, battery wear costs are minimum for this strategy with a correspondingly high battery lifetime. Overall, the storage batteries are underutilized since operating costs could be further reduced by more intelligent use of the batteries.

It is interesting to note that the Frugal Discharge Strategy results in less fuel usage than the Optimal Fixed-Threshold Discharge Strategy, even though the latter has a lower diesel running time. This illustrates the point that it is not merely total diesel running time that determines fuel usage. The Frugal Discharge Strategy more often uses storage batteries to meet higher values of net load than does the Optimal Fixed-Threshold Strategy. This results in reduced fuel consumption, but with a corresponding increase in battery usage. As a consequence, the total operating costs are less for the Optimal Fixed-Threshold Strategy.

6.2.4 Ideal Discharge Strategy

The effectiveness of the Ideal Discharge Strategy is due to the fact that it uses available excess wind energy in a manner that minimizes total diesel fuel consumption. Stored wind energy is always allocated to those net loads that will maximize savings. The relatively high battery wear costs are an indication that little stored wind energy is left unused. By making optimal use of stored wind energy, this strategy minimizes diesel running time, fuel consumption and overall operating costs.

6.2.5 Fuzzy Discharge

The Fuzzy Discharge Controller comes closest to matching the performance of the Ideal Discharge Strategy. It too makes use of stored wind energy to decrease diesel running time and fuel consumption. Its battery wear costs are relatively high; but, like the ideal strategy, these costs are more than compensated by the resulting savings in fuel usage. Since the Ideal Discharge Strategy is purely academic, the fuzzy controller can be said to the yield the best results of the practical discharge strategies considered.

6.3 Analysis of Assumptions

In Chapter 2, a number of assumptions in simplifying the analysis that followed were described. The implications of several of these are now addressed.

6.3.1 Diesel Generator Fuel Curve

It was assumed that the fuel consumption curve of the diesel generator could be approximated as a straight line rather than a more accurate quadratic curve. When simulations were repeated using the more realistic quadratic model to calculated fuel costs, no significant variations in the results were observed.

6.3.2 Storage System Efficiency

An overall round-trip storage efficiency of 80% was used in the simulations. It could be argued that this is an unrealistically high value, given that it comprises inefficiencies of the converter, inverter and storage batteries themselves. However, the effects of storage inefficiency are equally detrimental to all of the dispatch strategies presented. For example, Figure 6-6 shows the total operating cost for the various discharge strategies for a round-trip storage efficiency of 50%. From this it is obvious that the relative performances of each strategy are unaffected.

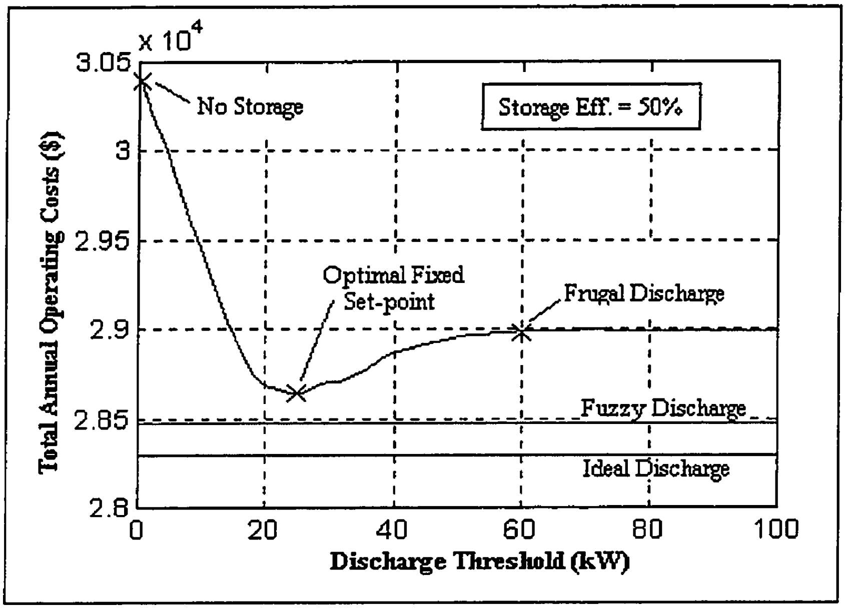

Figure 6-6 Total operating costs for a storage efficiency of 50%

However, it must be noted that lower storage efficiencies definitely result in increases in operating costs. This would be an important point to consider in a cost-benefit analysis aimed at determining whether to include some amount of long-term storage in a hybrid power system.

6.3.3 Diesel Engine Starts

The data of table 1 shows that the number of diesel starts does not differ greatly regardless of which discharge strategy is used. As the number of starts is in the order of one to two a day, the assumption that the related costs could be ignored is justified.

6.4 Effects of Inaccuracies in Wind Forecasts

The results cited in table 1 were obtained by simulating a perfect wind forecast as continuous input to the fuzzy controller. Recall that the wind input variable is a forecast of maximum hourly wind speed expected in the next 12 hour period. Obviously, a perfect prediction is not possible in real time. Additionally, the logistics of obtaining wind forecast information are not straightforward.

The ideal situation is to have a continuous source of wind forecasts. This might be supplied by an on-line connection to a source of meteorological information, for example. However, a more likely scenario is a periodic forecast obtained one or more times a day at specific intervals and input by a human operator. Alternatively, a seasonal forecast could be supplied to the controller, with the wind forecast being adjusted by the operator several times a year to reflect typical seasonal wind patterns. A third option would be to use a fixed input for the wind forecast variable based on analysis of wind patterns for previous years at the site. This variable could be set by the controller designer, and possibly allow for adjustment by an operator.

Table 3 displays simulated cost reductions of the Fuzzy Discharge Controller under various possible sources of wind forecast information. The savings are again calculated relative to the operating costs for no use of long-term storage.

Table 3 - Relative Reduction in Costs for Various Forecast Methods

Wind Forecast Source .	Operating Cost Reduction (%)
Continuous prediction with noise of 1/2 standard deviation	6.72
Daily fixed forecast	6.52
Monthly fixed forecast	6.36
Yearly average fixed forecast	6.49

When compared with the results of Table 2, it can be noted that the savings in each case are greater using the fuzzy controller than using the Optimal Fixed-Threshold Discharge Strategy.

It is fruitful to examine the performance of the fuzzy controller using a yearly average fixed forecast. In this case, as the forecasted wind speed variable is fixed for the entire year, the controller actually sees only one input variable – battery state of charge. The performance of the fuzzy controller is nevertheless better than any other practical discharge strategy presented. This suggests that it might be preferable to design a simpler fuzzy discharge controller that would use battery SOC as the only input. Such a controller would be simpler to implement with perhaps only a modest reduction in savings. Further study would be needed to assess the benefits of this approach.

6.5 Robustness of the Fuzzy Discharge Controller

As a means of assessing the robustness of the Fuzzy Discharge Controller, simulations were carried out under a variety of different conditions. The wind speed and system load were scaled to simulate various possible scenarios. Additionally, alternate wind and load profiles from other test sites were used. The alternate wind and load data were from two of the test sites used in the Hybrid2 simulation software. The various combinations of conditions tested were

1. Mean wind speed increased by 20%
2. Mean wind speed decreased by 20%
3. System load increased by 50%
4. System load decreased by 50%
5. All combinations of the above
6. Deering, Alaska test site load scaled to 55kW mean
7. Culebra, Puerti Rico test site wind data (mean 6.99 m/s)

These cases represent a range of wind/load ratios from 0.25 to 1.75. In all cases, the Fuzzy Discharge Controller performed better than any other practical discharge strategy in terms of minimizing operating costs. These results attest to the robustness of the fuzzy controller design.

6.6 Effect of Storage Capacity Size on Results

In the case study presented, a usable storage size of 150 kWhr was assumed for the entire analysis. This storage size was chosen rather arbitrarily. It is interesting to investigate how the results would be affected if a different size storage were used. Figures 6-7 and 6-8 show total operating costs for simulations using storage sizes of 75 kWhr and 300 kWhr respectively.

In both cases, it is clear that the Fuzzy Discharge Controller results in reduced costs compared with the other practical strategies considered. As the fuzzy controller was optimized for a storage size of 150 kWhr, is does not produce results quite as close to the ideal strategy for these other storage sizes. Presumably, the parameters of the fuzzy controller could be adjusted to improve performance for each of these cases. For example, a shorter wind forecast period might improve the results for the system with the smaller storage size.

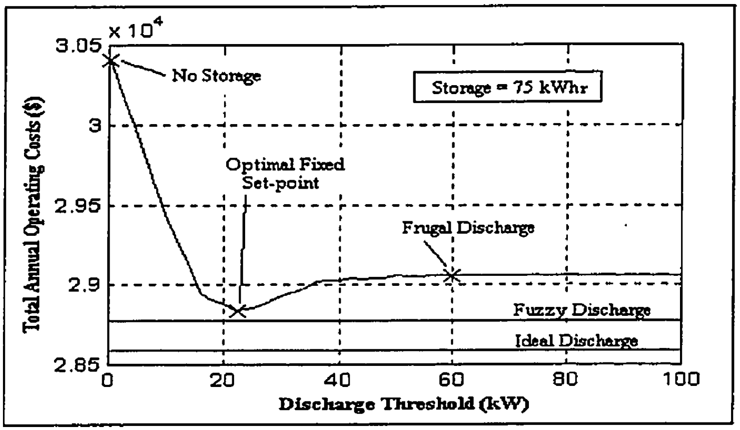

Figure 6-7 Results for a storage size of 75 kWhr

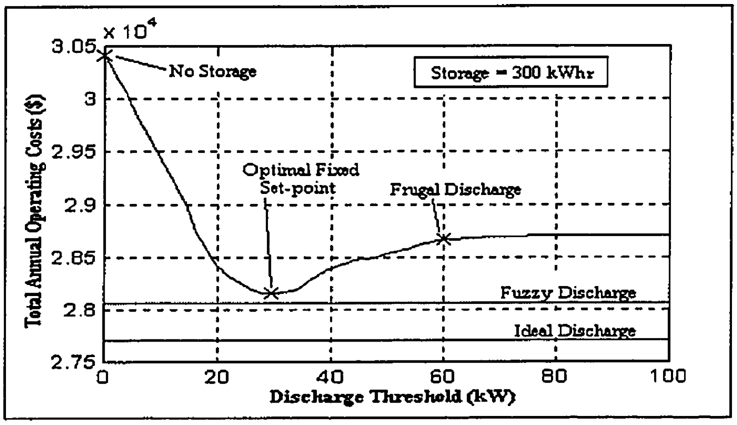

Figure 6-8 Results for a storage size of 300 kWhr

7. CONCLUDING REMARKS

This thesis has investigated the performance of various strategies for dispatching stored wind energy in a hybrid wind/diesel power system. Several strategies were presented and computer simulations were used to evaluate system performance in terms of reducing operating costs. In this chapter, implications of the results are briefly discussed and some aspects suitable for future research are suggested.

7.1 Conclusions

From the results presented, it is apparent that, for the type of hybrid power system investigated, the Frugal Discharge Strategy is neither the only nor the optimal method of dispatching stored wind energy. The theoretical Ideal Discharge Strategy showed the potential of increasing savings in operating costs through the judicious dispatch of stored energy. Two practical methods of implementing such improved discharge schemes were presented: the Optimal Fixed-Threshold Discharge Strategy and the Fuzzy Discharge Controller.

The Optimal Fixed-Threshold Discharge Strategy is simple to implement and, in the case study presented, increased savings significantly over the Frugal Discharge Strategy. This is an important finding since these two strategies differ from one another only in terms of the value of the discharge threshold. Thus it can be concluded that Optimal Fixed-Threshold Strategy should be favored.

The Fuzzy Discharge Controller uses a more sophisticated method to achieve further reductions in operating cost. The implementation of this strategy requires incorporating long-term wind speed prediction in the controller structure. Several possible methods of doing so were discussed; and it was shown that, generally, operating costs decreased with increased accuracy in the prediction method. In determining how best to implement this control strategy, the cost of incorporating a particular prediction scheme would have to be weighed against the potential increase in savings.

7.2 Future Research

The findings of this study suggest several areas for further research. It was noted in the case study that the fuzzy controller performed reasonably well, even when the wind prediction input was a fixed value. In this situation, the fuzzy controller was actually using only information about current battery state-of-charge in determining the discharge threshold. This suggests that a fuzzy controller could be designed using only this input. Perhaps such a controller could be optimized to achieve performance approaching that of the fuzzy controller presented here. Such a controller would be less costly to implement since it would not require the use of wind speed prediction.

The fuzzy controller presented uses wind speed forecasts alone as the basis for predicting future net load. Since system load variations also contribute to changes in net load (though to a lesser extent than wind speed variation in the case study presented), it may be possible to improve on the performance of the fuzzy controller by including a forecast of system load as an input variable. Since load variations generally follow fairly consistent daily and seasonal patterns, it can be expected that such a design approach would result in even greater operating cost reductions.

The scope of the study presented was limited to an investigation of battery discharge strategies, with the assumption that only excess wind energy would be used to charge the batteries. The system and cost parameters used in the case study were such that other charging mechanisms, such as cycle-charging, would not be cost effective. A more general analysis could be made by uniting the improved discharging strategies presented here with various battery charging strategies suggested elsewhere. This could lead to a generalized optimal storage strategy for hybrid wind/diesel systems.

Though this study investigated wind/diesel power systems, solar energy may be more favorable than wind energy in some locations. As the two types of hybrid power systems have much in common, it can be supposed that the results of this study would have parallels in a hybrid solar/diesel system. Further study would be needed to investigate the implications of this study on such systems.

REFERENCES

Baring-Gould, E. I. (1998). Hybrid2 the Hybrid System Simulation Model: Users Manual. National Renewable Energy Laboratory. Golden, CO.

Barley, C. D. (1996). Modeling and Optimization of Dispatch Strategies for Remote Hybrid Power Systems. Doctoral dissertation, Department of Mechanical Engineering, Colorado State University, Ft. Collins, Colorado.

Bleijs, J. A., Nightingale, C. J., & Infield, D. G. (1993). Wear implications of intermittent diesel operation in wind/diesel systems. Wind Engineering, 17(4), 206-219.

Bossanyi, E. A. (1985). Short-term wind prediction using Kalman filters. Wind Engineering, 9(1), 1-8.

Contaxis, G. C., & Kabouris, J. (1991). Short term scheduling in a wind/diesel autonomous energy system. Transactions on Power Systems, 6(3), 1161-1167.

Davies, T. S., Jefferson, C. M., & Mayer, R. M. (1988). Use of flywheel storage for wind diesel systems. Journal of Wind Engineering and Industrial Aerodynamics, 27, 157-165.

Infield, D. G., Slack, G. W., Lipman, N. H., & Musgrove, P. J. (1983). Review of wind/diesel strategies. IEE Proceedings, 130(9), 613-618.

Kariniotakis, G. N., Stavrakakis, G. S., & Nogaret, E. F. (1996). Wind power forecasting using advanced neural network models. IEEE Transactions on Energy Conversion, 11(4), 726-767.

Kosko, B. (1997). Fuzzy Engineering. Upper Saddle River, New Jersey: Prentice-Hall.

Lee, C. C. (1990). Fuzzy logic in control systems: fuzzy logic controller - Part I. IEEE Transactions on Systems, Man, and Cybernetics, 20(2), 404-418.

Linders, J. (1989). Some aspects of wind diesel systems with reference to Chalmers experimental wind diesel system. Wind Engineering, 13(3), 132-142.

Lipman, N. H. (1984). An analysis of the integration problem for wind power inputs into small grid systems. Wind Engineering, 8(1), 9-18.

Lipman, N. H. (1988). Autonomous wind-diesel systems for remote applications. Wind Engineering, 12(3), 173-193.

Little, T. A. (1995). Optimal Use of Energy Storage for a Wind/Diesel Grid. Doctoral dissertation, Department of Electrical Engineering, University of New Brunswick, Fredericton, New Brunswick, Canada.

Lynette, R., & Gipe, P. (1994) Commercial wind turbines and applications. In D. A. Spera (Ed.) Wind Trubine Technology. New York: Asme Press.

Musgrove, A. (1987). The optimisation of hybrid wind energy conversion systems for remote area power supply. Fifth International Conference of Energy Options, 115-119.

Nayar, C. V., Lawrance, W. B., & Phillips, S. J. (1989). Solar/wind/diesel hybrid energy systems for remote areas. IEEE Publication No. CH2781-3/89/0000-2029, 2029-2034.

Reid, R. (1992). The high penetration no storage wind/diesel scenario: A proposed demonstration program. 1992 AWEA/CanWEA Wind/Diesel Workshop. Mill River, Prince Edward Island, Canada

Ross, T. J. (1995). Fuzzy Logic with Engineering Applications. New York, NY; McGraw-Hill.

Saulnier, B., Reid, R., & Yves, J. (1993). Progress on the high penetration no-storage wind diesel demonstration project. 7th International Wind Diesel Workshop. Waitsfield, Vermont.

Sinha, A. (1991). A model of a combined WECS/hydro/dieselpower system with pumped storage. Wind Engineering, 15(1), 25-39.

Skarstein, O., & Uhlen, K. (1989). Design considerations with respect to long-term diesel savings in wind/diesel plants. Wind Engineering, 13(2), 72-87.

Spiers, D. J., & Rasinkoski, A. A. (1996). Limits to battery lifetime in photovoltaic applications. Solar Energy, 58(4-6), 147-154.

Tripathy, S. C., Kalantar, M., & Balasubramanian, R. (1991). Dynamics and stability of wind diesel turbine generators with superconducting magnetic energy storage unit on an isolated power system. IEEE Transactions on Energy Conversion, 6(4), 579-585.

Van der Hoven, I. (1956). Power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour. Journal of Meteorology, 14, 160-164.

Wang, L. (1994). Adaptive Fuzzy Systems and Control: Design and Stability Analysis. Englewood Cliffs, NJ: Prentice-Hall.

Watson, G. R. (1987). Operational experience of hybrid wind-diesel systems. Wind Engineering, 11(2), 107-113.

APPENDIX A: PROGRAM LISTINGS

The following programs were used in the simulations in preparing this thesis:

perform_diesel.m	Program to calculate fuel usage and number of starts of diesel generator
fixed_discharge.m	Program to simulate system performance with a fixed discharge threshold strategy
ideal_discharge.m	Program to simulate system performance with Ideal Discharge Strategy
discharge_rate.m	Function used by ideal_discharge.m program to determine ideal hourly discharge rate for batteries
fuzzy_discharge.m	Program to simulate system performance with the fuzzy discharge controller
discharge.fis	Parameters of the fuzzy inference matrix used in the fuzzy discharge controller.

Program Input Variables:

frugal_thres = frugal discharge threshold from eqn. (3.2), kW

look_ahead = amount of time on which wind forecast is based, h

p_net = array of hourly system net load (load – wind power), kW

p1 = array of hourly diesel generator output powers, kW

thres = threshold of maximum net power for battery discharge, kW

wind = array of hourly average wind speeds, km/hr

Program Output Variables:

batt_out = total amount of power delivered by batteries, kWhr

fuel = total amount of diesel fuel used, l

p = array of hourly diesel generator output powers, kW

starts = total number of diesel generator starts

store = array of hourly battery charge levels, kWhr

Program Working Variables:

batt_eff = storage system round-trip efficiency

capacity = useable storage capacity of batteries, kWhr

conv_limit = storage converter maximum continuous power limitation, kW

f_0 = diesel generator fuel consumption rate, l/hr

f_l = diesel generator fuel consumption at no load, l/hr

self_discharge = hourly battery self-discharge factor

Note: Comments in the code are in italics.

perform_diesel.m

```
% Function to calculate the total amount of fuel used (in liters) and the total number
% of diesel starts for the array of diesel generator power outputs p1.
% Diesel generator rating is 100kW and a dispatch time is 1 hr

function [fuel,starts]=diesel_perform(p1)

   % ********* calculate fuel consumption **********

f0=8.415;                    % fuel consumption parameters in liters/kWhr
f1=0.246;

                             % calculate amount of fuel used by the generator
fuel= f0 + f1*p1;

fuel=fuel.*(p1~=0);          % if(p1(i)==0) then  fuel(i)=0; else fuel(i) =f0+f1*p1

fuel=sum(fuel);

    % ********* calculate number of stops for the diesel *********

p1_old=p1;
p1=p1(2:length(p1));
p1=[p1,1];                   % so p1 and p1_old have equal number of elements

starts= sum(p1_old==0 & p1 ~=0);
```

fixed_discharge.m

```
% Function to determine performance for a low-following strategy with a fixed
% discharge threshold (thres). 1 hr dispatch

function[p, store, batt_out]=fixed_discharge(thres, p_net)

global capacity;
global conv_limit;
global batt_eff;
global self_disc;

store=zeros(1, length(p_net)+1);        % array of battery storage

batt_out=zeros(1, length(p_net));       % array of battery discharge

store(1)=capacity;                      % assuming batteries start fully charged

for i=[1:length(p_net)]
        if p_net(i)<=0;                 % then charge batteries if not fully charged
                p_charge=min(conv_limit/batt_eff, -p_net(i));
                p_charge=p_charge*batt_eff;
                tore(i+1)=self_disc*store(i)+p_charge;
                store(i+1)=min(store(i+1), capacity);  % cannot exceed batt capacity
                p(i)=0;                 % diesel gen is off

        else                            % then net load must be met by batt or diesel

        if (p_net(i)<=thres & store(i)-p_net(i)>=0)
                                        % if load is below discharge threshold & batts
                                        % have enough power to meet the load then
                                        % use batts to meet the load
                store(i+1)=self_disc*(store(i)-p_net(i));
                batt_out(i)= p_net(i);
                p(i)=0;                 % diesel gen is off

        else                            % diesel must meet the load
                store(i+1)=self_disc*store(i);
                p(i)=p_net(i);
        end
   end
end
```

ideal_discharge.m

```
% Function to implement Ideal Discharge Strategy and determine  performance of the
% system

function[p, store, batt_out]=ideal_discharge(frugal_thres, p_net);

global capacity;
global conv_limit;
global batt_eff;
global self_disc;

p_net_temp=p_net;

charge=batt_eff*min(conv_limit/batt_eff, -p_net).*(p_net<0);
                                        % recharging power from wind

p_net=p_net.*(p_net>=0);                % to get rid of negative p_nets

p_disc=zeros(1, length(p_net));         % array of discharge rates
max_pnet=max(p_net);

for i=[1:length(p_net)]
        index=min(find(p_net==min(p_net))); % index of first min p_net in array

           % call function to determine if batts should be used to meet this hour of load
        p_disc(index)=discharge_rate(index, p_net, p_disc, charge, frugal_thres);
        p_net(index)=2*max_pnet;   % so that we don't consider this hour again
end

p_net=p_net_temp;               % restore original p_net array

store=zeros(1, length(p_net)+1);

store(1)=capacity;
                                        % construct array of batt charge
for i=[1:length(p_net)]
        store(i+1)=self_disc*(store(i)-p_disc(i))+charge(i);
        store(i+1)=min(store(i+1), capacity);
end

p=(p_net.*(p_net>=0)-p_disc')';         % diesel generator power
batt_out=sum(p_disc);  % total battery energy used
```

discharge_rate.m

```
% Function to determine whether a particular net load, p_net(index), should
% be met by battery or by diesel.  Returns rate=0 if diesel should be used, and
% rate=p_net(index) if batteries should be used.

function[rate]=discharge_rate(index, p_net, p_disc, charge, frugal_thres)

global capacity;
global self_disc;

store=zeros(1, length(p_net)+1);

store(1)=capacity;

for i=[1:length(p_net)]
        store(i+1)=self_disc*(store(i)- p_disc(i)-(i==index)*p_net(index)) + charge(i) ;
        store(i+1)=min(capacity, store(i+1));
end

                        % find minimum value of batt charge for entire period
x=min(store(index:length(store)));

rate=(x>=0 & p_net(index)<frugal_thres)*p_net(index);
                        % if no batt charge is <0 and p_net(index)<frugal thres, then
                        % rate=p_net(index), else rate=0
```

fuzzy_discharge.m

```
% Function to determine performance for a low-following strategy with a fuzzy
% discharge. 1 hr dispatch.

function[p, store, batt_out]=fuzzy_discharge(look_ahead, p_net,wind)

global capacity;
global conv_limit;
global batt_eff;
global self_disc;

fis_matrix=readfis('discharge');        % read FIS for fuzzy controller

store=zeros(1, length(p_net)+1);        % array of battery storage

batt_out=zeros(1, length(p_net));       % array of battery discharge

store(1)=capacity;                      % assuming batteries start fully charged

mean_wind=mean(wind);


for i=[1:length(p_net)]
        if i+look_ahead>length(p_net)         % to handle end of simulation period
                next_wind=mean_wind;
        else
                next_wind=max(wind(i:i+look_ahead));
        end
                        % call fuzzy inference engine to calculate discharge thres
        thres=evalfis([100*store(i)/capacity, next_wind], fis_matrix);

        if p_net(i)<=0;                       % then charge batteries if not fully charged
                                              % so charge batteries
                p_charge=min(conv_limit/batt_eff, -p_net(i));
                p_charge=p_charge*batt_eff;

                store(i+1)=self_disc*store(i)+p_charge;
                store(i+1)=min(store(i+1), capacity);   % cannot exceed batt capacity

                p(i)=0;                                 % diesel gen is off

        else                                  % net load must be met by batt or diesel
```

```
                if (p_net(i)<=thres & store(i)-p_net(i)>=0)
                                        % if load is below discharge threshold & batts
                                        % have enough power to meet the load
                        store(i+1)=self_disc*(store(i)-p_net(i));
                        batt_out(i)= p_net(i);
                        p(i)=0;                                 % diesel gen is off
                else                                    % diesel must meet the load
                         store(i+1)=self_disc*store(i);
                        p(i)=p_net(i);
                end
        end
end
```

discharge.fis

```
[System]
Name='discharge'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=9
AndMethod='prod'
OrMethod='max'
ImpMethod='prod'
AggMethod='sum'
DefuzzMethod='centroid'

[Input1]
Name='SOC'
Range=[0 100]
NumMFs=3
MF1='low':'trimf',[-20 0 20]
MF2='med':'trimf',[0 20 95]
MF3='high':'trapmf',[20 95 105 150]

[Input2]
Name='wind'
Range=[0 100]
NumMFs=3
MF1='low':'trapmf',[-20 0 15 35]
MF2='med':'trimf',[15 35 50]
MF3='high':'trapmf',[35 50 100 150]

[Output1]
Name='thres'
Range=[-10 60]
NumMFs=6
MF1='0':'trimf',[-10 0 10]
MF2='10':'trimf',[0 10 20]
MF3='20':'trimf',[10 20 30]
MF4='30':'trimf',[20 30 40]
MF5='40':'trimf',[30 40 50]
MF6='50':'trimf',[40 50 60]
```

```
[Rules]
1 1, 1 (1) : 1
1 2, 1 (1) : 1
1 3, 3 (1) : 1
2 1, 2 (1) : 1
2 2, 2 (1) : 1
2 3, 4 (1) : 1
3 1, 3 (1) : 1
3 2, 4 (1) : 1
3 3, 6 (1) : 1
```