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Integration of Wind-Turbine Generators (WTGs) into Hybrid Distributed Generation Systems in Extreme Northern Climates

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Abstract: - This paper discusses the effects of integrating wind-turbine generators (WTGs) into hybrid distributed generation systems in extreme northern climates. The hybrid performance analysis tool presented incorporates the added features of dynamic modeling and the graphical user interface available in MATLAB™ Simulink. The model currently consists of a diesel-electric generator, a battery storage bank, and WTGs connected to a common grid to form the hybrid system. The work presented in this paper studies the long-term performance issues related to integrating a WTG into hybrid electrical power systems in rural villages of Alaska. An example is presented based on an actual test system in the remote Alaskan coastal community of Wales Village. The simulation results were compared with those predicted by HOMER developed at NREL. The Life Cycle Cost (LCC) and air emissions results of our Simulink model were comparable to those predicted by HOMER.

Keywords: - Battery storage, Diesel generator, Hybrid power system, Wind-turbine generators

1 Introduction

WITH the growing demand for energy, increasing concerns for environmental pollution and rising oil prices, efforts are being taken by governments around the world to implement renewable energy programs. These programs include the integration of renewable resources such as wind, solar, biomass, geothermal, and small hydro-electric power. Due to its competitive cost of energy compared to fossil fuel, wind power is proving to be the fastest growing, cost effective and reliable renewable energy source of electricity in the remote areas around the world. It is estimated that the wind could supply 12 percent of the world's electric demand by 2020 [1].

The cost and efficiency of electric power in remote villages is of great concern. This topic is very important for Alaska, which has more than 200 remote communities [2], for developing countries such as Mexico, which has approximately 86,000 villages each with a population less than 1000 persons [3] and for Asia, where 70% of the villages have no access to the electric utility grid [4]. In such locations, stand-alone power systems are often more cost-effective than utility grid extensions mainly due to the high cost of constructing transmission lines for such a small remote load. Most of the remote Alaskan communities have no access to the main electric utility grid and rely on diesel electric generators (DEGs) for electric power. Fuel is also very expensive for DEGs in these locations due to the transportation costs and often times the only means of transportation is by air [5, 6]. Furthermore, there are issues associated with oil spills and storage of this fuel [6]. According to the United States Department of Energy (USDOE), Alaska spends $28.71 per million BTU for energy as compared to $19.37 per million BTU for the United States [7]. The integration of renewable power sources with DEGs in remote locations can substantially reduce the cost of power by reducing fuel consumption, increasing the efficiency of the overall system and reducing emissions.

Recently, there has been a very strong interest by the utility companies in renewable energy conversion systems. The main reasons for this interest are reduced fuel consumption, increased system efficiency, and reduced emissions [8, 9]. Utilization of renewable energy sources helps bring down the cost for fuel or other non-renewable energy sources. For example, in Kotzebue, Alaska, ten 15/50 AOC (Atlantic Orient Corporation) wind turbines are installed. Each turbine is estimated to meet 5% of the system load [10].

It is necessary to study the performance of hybrid power generation systems in remote communities in order to optimize the cost, efficiency, and emissions of these systems when operated in these environments. The goal of the work presented in this paper is to investigate the long-term performance of a hybrid power system in the remote Alaskan community of Wales Village using the hybrid performance analysis tool developed in MATLAB™ Simulink. The Life Cycle Cost (LCC) and air emissions results of the Simulink model are compared with those predicted by Hybrid Optimization Model for Electric Renewables (HOMER) developed at the National Renewable Energy Laboratory (NREL).

2 Wales Village Power System

Hybrid electric power systems in remote villages of Alaska have been under development in recent years. This paper investigates the integration of a WTG with a diesel-battery hybrid electric power system located in Wales Village, Alaska. The Wales Village power system consists of 3 DEGs. One generator is sufficient to meet the entire load of the village and the other two generators are used as back-up generators. Diesel #1 is a 1200 RPM Cummins LTA10 rated at 168 kW, Diesel #2 is an 1800 RPM Allis-Chalmers 3500 rated at 75 kW, and Diesel #3 is another 1200 RPM Cummins LTA10 rated at 168 kW. Although there are three diesels, the plant is operated as a single-diesel plant. Either Diesel #1 or Diesel #3 is operated exclusively. The other diesel is brought on-line during oil changes or other maintenance procedures. Diesel #2 is less efficient than the larger diesels and is operated only if both of the other generators are shut down.

The hybrid model of Wales Village also consists of two 65kW 15/50 Atlantic Orient Corporation (AOC) wind turbines (spaced 500 feet apart), two hundred 1.2-volt SAFT SPH130 plastic bonded electrode nickel cadmium batteries connected in series for an overall rating of 240VDC and 40 kWhr, and a 156 kVA rotary converter to convert the DC power from the battery bank to AC power. Since the battery bank is currently used as back-up power, the system has a 300VDC, 30A auxiliary battery charger. The system also consists of 255 kW of optional resistive heating load (dump loads) with associated dump load controllers connected to the main system controller.

Figures from NREL show the average cost of fuel supplied to Wales Village was about $3/gallon ($0.7936/liter) in 2001. Therefore, it is desired that the diesel generators operate efficiently and economically [6]. The use of renewable energy in the form of WTGs combined with regulated battery storage helps in constraining the use of the diesel generator while optimizing the efficiency and economics of the system [11].

3 Simulink Model

A model of the hybrid power system at Wales Village was designed using MATLAB™ Simulink as shown in Fig. 1. The model is based on previous work for a photovoltaic (PV) with diesel-battery system presented in [12] and [13]. The model consists of nine different subsystems contained in blocks. The *Input Parameters* block includes all of the necessary binary data files required to run the simulation. This information is used by all of the other subsystems to calculate electrical efficiency, fuel consumption, and fuel cost.

The Simulink model is designed to obtain the data from the *Input Parameters* block every 1-minute. The model is designed for 1-minute time interval so as to incorporate the system dynamics in the future. This 1-minute time increment can be easily changed in Simulink. Currently, the Simulink model studies the long term performance including the environmental impact calculations of the hybrid power system under consideration.

The different inputs required by the *Input Parameters* block includes the annual load profile, the annual power factor, the annual wind speed for the wind turbines, the annual ambient temperature under which the power system is operating, the kW ratings of the generators, and the kW rating of the battery bank.

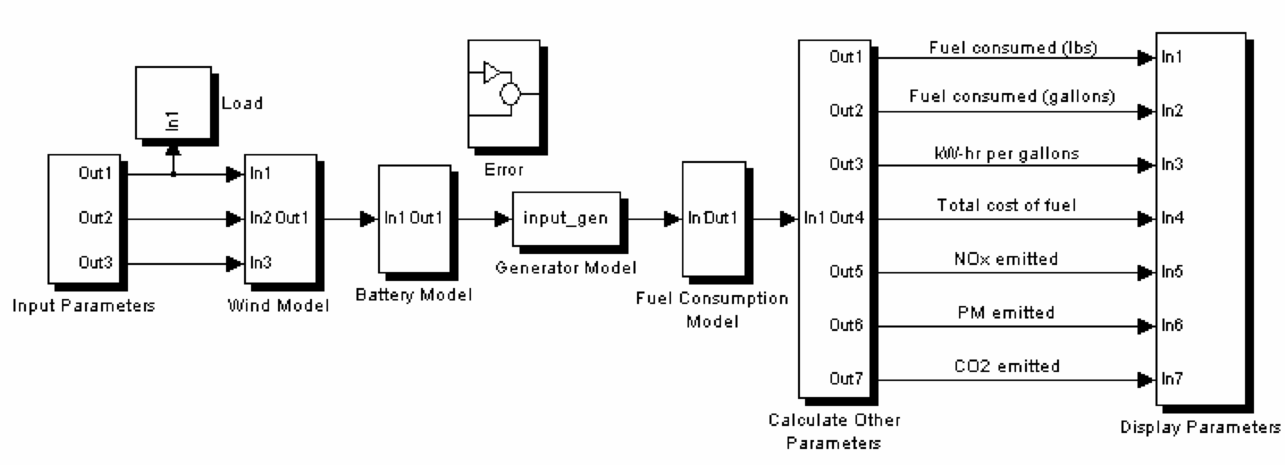

Fig. 1. Simulink model of the Wales Village power system.

The hybrid power system is designed in such a way that the *Wind Model* has the highest priority to supply the load. If the load is not met by the WTGs, the battery bank is used to supply the required load, and if the battery bank is less than 20% charged, the controller sends a signal to the diesel generator to turn "on" and the diesel generator is then used to supply the desired load and charge the batteries at the same time. On the other hand if there is excess power available from the WTGs, the excess power is sent to a dump load which can be used for space heating purposes.

It should be noted that there is a high demand for heating load in remote communities of Alaska, including Wales Village. The model is currently designed for two DEGs and two WTGs, but can be extended if desired. The operation of the Simulink model is described in more detail in the subsequent sections. The *Wind Model* block is the model of the 15/50 AOC wind turbines. The block takes the system load, and the wind speed as the input to the block. This block then calculates the power available from the two WTGs depending on the speed of wind based on a look-up table. The look-up table for the WTGs is obtained from the manufacturer's data sheet.

The *Battery Model* block consists of the battery bank and the controller. The *Battery Model* has the second highest priority to supply the load. The input to the block is the unmet load obtained from the output of the *Wind Model* block. The block checks the charge on the battery bank. If there is not enough energy to supply the load, the controller sends a signal to the diesel generator to turn "on". The diesel generator then supplies the load and charges the battery bank simultaneously. The battery bank model takes the charge and discharge rates for extreme cold temperatures into consideration [14]. The controller regulates the flow of power between the battery bank, the WTGs and the diesel generator.

The *Generator Model* block contains the manufacturer's specifications for the efficiency of the electric generator at various displacement power factors (DPF) for a given load. The DPF is the cosine of the angle between the voltage waveform and the first component of the current harmonics (DPF = $\cos(\Phi_1)$). For a perfectly sinusoidal current waveform DPF is same as power factor. This data is obtained from the performance curve of the diesel generator. Knowing the load on the generator and the efficiency, the power input to the electric generator can be calculated as

$$P_{Input} = P_l/\eta \tag{1}$$

where P_l is the load on the generator and η is the efficiency.

The *Generator Model* block is designed in such a way that the DEGs always operate at 95% of their kW rating while operating in conjunction with the battery bank and the WTGs. In this way the DEGs operate at their maximum efficiencies. If one generator is insufficient to supply the load, the second generator is turned "on". In Wales Village, for the given load profile, one generator is able to supply the load. In the event that a second generator is required, rather than operating one generator at full load and the other at a very small load, the model is designed so that both the generators operate at 95% of their rated load and the excess energy is used to charge the battery banks.

The *Fuel Consumption Model* block calculates the amount of fuel required by the diesel engine to supply the load. The fuel consumed by the engine depends on the load and the efficiency of generator, which in turn depends on the DPF of the load. If there are two generators operating, the block will calculate the fuel required by each engine and also the total fuel required to supply the load. The plot for the fuel consumption versus the input power to the electric generator is obtained from manufacturer's data sheet as previously discussed. This plot is interpreted mathematically as follows:

$$\text{Fuel consumed (Lbs)} = G * P_{Input} + C \quad (2)$$

$$\text{Fuel consumed (gallons)} = \frac{\text{Fuel consumed (Lbs)}}{6.7} \quad (3)$$

where P_{Input} is the input power to the generator given in kW, G is the gain for the engine and C is the constant obtained from the performance curve of the diesel engine in the manufacturer's data sheet. The value of G depends on the capacity of the diesel generator and the value of C is the no-load fuel consumed by the diesel engine. The value of 6.7 (#2 diesel fuel) is the number of pounds (lbs) of fuel per gallon and depends on the type of fuel used.

The *Calculate Other Parameters* block calculates the parameters like the total kWhrs/gallon supplied by the generator, the fuel consumed in lbs, the fuel consumed in gallons, the total cost of fuel in USD, the amount of CO_2 emissions, the amount of particulate matter (PM_{10}) emissions, and the amount of NOx emissions.

$$\text{kWhrs/gallon} = \frac{kWhr_{Gen}}{F_C} \quad (4)$$

$$\text{Total cost (\$)} = F_C * \text{cost/gallon} \quad (5)$$

$$\text{Total } CO_2 = CO_2/kWhr_{Gen} * kWhr_{Gen} \quad (6)$$

where $kWhr_{Gen}$ is the total kWhr supplied by the diesel generator and F_C is the total fuel consumed in gallons. The quantity cost/gallon is the cost of fuel (USD) per gallon and varies for different locations. The CO_2 emissions are estimated as 1.75 pounds/kWhr and depend on the fuel composition and engine efficiency. The corresponding values for PM and NOx emissions can be obtained from the manufacturer using relationships similar to equation (6).

The *Display Parameters* block is used to display all the calculated parameters including the fuel consumption, the total cost of fuel and the kWhrs/gallon.

The 24-hour summer load profile recorded from Wales Village on August 06th, 2002 from 00:09 hours to 23:59 hours at 15-minute intervals is shown in Fig. 2. The annual load profile was used to study the performance of the hybrid power system. As the Simulink model is designed with 1-minute time increments, the 15-minute load data is linearly interpolated using Simulink to produce a load profile with 1-minute increments.

Simulations of the Wales Village hybrid power system were performed for the wind with diesel-battery system using the annual load profile. In the Simulink model as WTG provides energy from a renewable source, they have the highest priority to supply the load. The battery bank has the second highest priority. If the battery bank is incapable of supplying the load, the diesel generator is used to supply the load and charge the battery bank at the same time.

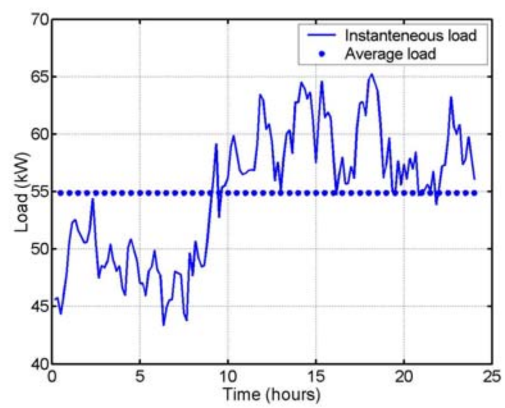

Fig. 2. 24-hour summer load profile for Wales Village.

4 Simulation Results and Discussion

The Simulink model for the wind with diesel-battery system was used to study the performance of the Wales electric utility. The plot for the power obtained from the WTGs at Wales Village on August 06th, 2002 from 00:09 hours to 23:59 hours recorded at 15-minute intervals is shown in Fig. 3.