Modeling and Performance Analysis of an Integrated Wind/Diesel Power System for Off-Grid Locations

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Abstract – This paper presents the modeling and performance analysis of wind/diesel hybrid generating system. Such configurations are typical for remote rural communities which are disconnected from the larger power grid, such as those located on islands or in forests. Controllers are designed to ensure operation of the wind and diesel units in a cooperative manner, in order to reduce the fossil-fuel consumption of the diesel generator. The system has been simulated using PSCAD/EMTDC for different wind speed variations.

I. INTRODUCTION

Driven by increasing costs and decreasing reserves of fossil-fuels, as well as by global environmental concerns, renewable energy is becoming a significant fraction of the total energy generation. Rapid advances in wind turbine generator technologies have brought opportunities for increased utilization of wind energy for electric power generation around the world. By the end of January 2008, world-wide installed wind nameplate capacity was 90,419 MW [1]. The major utilization of these wind capacity installations is in large grid connected electric power systems. However, there exist technological and economical advantages associated with wind energy, which justifies the use of wind energy in small scale stand alone applications for remote isolated communities.

There are many remote communities around the world which are physically or economically difficult to connect to an electricity grid. In many locations, such as in Northern Canada, such remote and isolated communities solely depend on conventional diesel fuel for their electricity supply. Diesel generation in these locations is expensive not only due to the escalating cost of the fuel itself, and also due to the fuel transportation costs and equipment maintenance costs. On the other hand, the wind speed in those remote areas is often fairly high and hence wind energy has huge potential. Wind energy based systems require no fuel cost and can, therefore, be included in these conventional small isolated systems in order to replace the costly diesel fuel by renewable energy. From an energy production point of view, it is desirable to have as much wind energy production as possible in order to save fuel consumption of the diesel engines and to reduce the level of pollution.

A great deal of effort has been devoted to wind energy studies especially to large grid connected wind energy applications [2-5]. Considerably less work, however, has been done on wind energy operating impacts on small isolated systems especially on wind/diesel systems.

A simple and common method of using wind energy in remote areas is to operate the wind turbine generator in parallel with diesel generators in order to reduce the average diesel load and hence save fuel. This mode of operation is particularly suitable for systems with relatively small renewable energy penetrations. Another possible mode of operation that is also effective in overall fuel savings is to run a back-up diesel intermittently to make up during sudden power shortages.

This paper presents the modeling and performance analysis of wind/diesel hybrid power system investigated for location at a typical remote community in northern Manitoba, Canada. The wind turbine drives an induction generator and the diesel engine driving a synchronous generator. The discussion starts with the system modeling. Details of the dynamic simulation models and the sample transient and steady-state results are presented. Controllers are designed to operate the diesel generator in an economical way to reduce the fuel consumption. The entire system has been tested for different wind speed variations using PSCAD/EMTDC.

II. SYSTEM MODELING

The wind/diesel system of interest to be modeled is shown in Fig.1. An isolated village load, typical of isolated communities in Northern Canada, is supplied through a wind turbine and a diesel generator simultaneously. As indicated by the arrows, both the wind turbine and the diesel generator modules generate power. The powers flowing in the system are indicated as $P_W$ (wind turbine output power), $P_D$ (diesel generator output power) and $P$ (total power going into the village load.)

The wind-diesel hybrid system is commonly applied in remote areas where there is a constant wind source. When the demand is low, the wind power is used to supply the load. The diesel generators are only used when the customer demand is high. In this case, the wind power is also used to supply the demand in order to save the diesel fuel consumption provided there is enough wind to produce electricity. If there is a shortfall in the availability of the wind source, the diesel generator picks up the slack.

Wind turbines produce a level of power dependant on the wind passing the rotor at any given instant. Because wind is variable in nature, the wind turbine’s power output can have fluctuations. The proportion of wind power relative to the load demand (wind power penetration level) determines the level of control required for a stable electrical system with good power quality. In order to harness the power of a diesel generator, it must be operating in a warmed-up condition. Also, a minimum load levels has to be maintained. Typically, a diesel generator has to be operated with at least 40% of the load. In case of very low loads, the operating temperature will be low which lead to increased corrosion and oil contamination.
**A. Wind Turbine Model**

The power extracted from the wind is given by [6]

\[ P = 0.5 \rho C_p W_v^3 A_s \]  

where
- \( P \): power, Watt
- \( \rho \): density of air, kg/m\(^3\) (high density air results in more power)
- \( W_v \): wind speed, m/s (doubling of wind speed results in 8 fold increase in power)
- \( C_p \): coefficient of performance (different types of wind turbines have different maximum theoretical efficiencies but usually between 0.4 and 0.5)
- \( A_s \): swept area of the wind turbine blades in m\(^2\) (a slight increase in blade length, increases the area greatly).

Induction generators are very popular in wind turbine applications. They are reliable and well developed. Additionally, induction generators are loosely coupled devices, i.e., they are heavily damped and therefore have the ability to absorb slight changes in rotor speed whilst remaining connected to the grid. The operation of the induction machine is determined from the sign of the electromagnetic torque and the slip, that is negative torque and slip correspond to generator operation whereas positive torque and slip correspond to motor operation.

The MOD-2 wind turbine generator model [7] has been used in the simulation. The model determines the turbine’s output torque \((T)\) given the wind speed \((W_v)\), the machine speed \((W)\) and the pitch angle \(\beta\). The blade dynamics are approximated by the following equations:

\[ \omega_H(W) = \frac{W}{GR} \]  

(2)

\[ \gamma(W, W_v) = \frac{W_v}{\omega_H(W)} \]  

(3)

Power coefficient:

\[ C_p(W, \beta) = \frac{1}{2} \left[ \gamma(W) - 0.022 \cdot \beta^2 - 5.6 \right] e^{-0.17 \gamma(W)} \]  

(4)

Power output in per unit:

\[ P(W, \beta) = \frac{1}{2} \cdot \rho \cdot A_s \cdot W_v^3 \cdot C_p(W, \beta) \cdot G_{eff} \]  

\[ \cdot \frac{1}{1000000 \cdot G_{MVA}} \]  

(5)

Torque in per unit:

\[ T(W, \beta) = \frac{P(W, \beta) \cdot W_{RAT}}{W \cdot pp} \]  

(6)

where
- \( W \): machine mechanical speed in rad/s
- \( GR \): gear ratio
- \( \beta \): pitch angle in degrees
- \( G_{eff} \): gear box efficiency
- \( G_{MVA} \): machine rated MVA
- \( W_{RAT} \): rated speed of machine in electrical rad/s
- \( pp \): pole pairs.

**B. Wind Source Model**

A four-component wind model has been used in this paper that allows representation of base wind velocity, gust wind component, ramp wind component and noise wind component [7]. The mean wind speed at a reference height will be entered within the component and the external input (Es) can be used to input any type of wind variation. Actual wind pattern recordings from field tests can also be imported and be used as the wind speed to the turbine model.

**C. Diesel Generator Model**

At the present stage of modeling, the dynamics of the prime mover diesel engine is not fully represented. The controller for the engine is a simple speed governor that keeps the turbine operating at its designed speed. The output of the speed governor is throttle signal that controls the fuel going into the engine. This is fed to a first order lag representing the engine itself. The output of this block is the mechanical torque applied to the synchronous generator. The power output from the synchronous generator is per-unitized based on the rated power level of the machine.

A salient-pole synchronous generator model based on d-q axis theory is used to model the electric generator [8]. The model is a seventh order model and allows representation of transient and sub-transient effects as well as machine saturation. The machine has an IEEE type solid-state exciter [9]. The output field voltage is varied by a control system to maintain the system voltage at a reference (Vref).

**D. Load Model**

The fixed P/Q load of 1 MW, 0.95 power factor with rated voltage 13.8 kV (L-L, rms) is considered in the study. The load is connected into the 13.8 kV distribution network of the serviced community. The load is modeled as a fixed impedance load [9].

**III. SYSTEM DESCRIPTION**

To evaluate the performance of the wind/diesel hybrid power system, an isolated village load of 1 MW has been considered. It is assumed that the diesel generator is supplying 70% of the total load while the remaining 30% is supplied through the wind turbine. The load is connected to the diesel generator and the wind turbine through short overhead transmission lines of length 0.9 km and 2.5 km respectively.
### TABLE I

**SYNCHRONOUS MACHINE PARAMETERS**

<table>
<thead>
<tr>
<th>System quantities</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base angular frequency</td>
<td>376.99 rad/s</td>
</tr>
<tr>
<td>Rated power</td>
<td>1.0 MVA</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>9 kV (L-L, rms)</td>
</tr>
<tr>
<td>Inertia constant</td>
<td>1.7 s</td>
</tr>
<tr>
<td>Smoothing time constant</td>
<td>0.02 s</td>
</tr>
<tr>
<td>Terminal voltage magnitude at start-up</td>
<td>1.05 per unit</td>
</tr>
<tr>
<td>Terminal voltage phase at start-up</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### TABLE II

**INDUCTION MACHINE PARAMETERS**

<table>
<thead>
<tr>
<th>System quantities</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base angular frequency</td>
<td>376.99 rad/s</td>
</tr>
<tr>
<td>Machine rated angular mechanical speed</td>
<td>1200 rpm</td>
</tr>
<tr>
<td>Rated terminal voltage</td>
<td>9 kV (L-L, rms)</td>
</tr>
<tr>
<td>Rated power</td>
<td>0.5 MVA</td>
</tr>
<tr>
<td>Stator/rotor turns ratio</td>
<td>1</td>
</tr>
<tr>
<td>Angular moment of inertia</td>
<td>3.0 s</td>
</tr>
<tr>
<td>Mechanical damping</td>
<td>0.0005 per unit</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>0.0043 per unit</td>
</tr>
<tr>
<td>Wound rotor resistance</td>
<td>0.002 per unit</td>
</tr>
<tr>
<td>Magnetizing inductance</td>
<td>3.0 per unit</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>0.0613 per unit</td>
</tr>
<tr>
<td>Wound rotor leakage inductance</td>
<td>0.0613 per unit</td>
</tr>
</tbody>
</table>

A synchronous generator of 1 MVA and a wound rotor induction machine of 0.5 MVA rating have been used for diesel and wind turbine respectively. The detailed machine data is given in Tables I and II. The other system parameters (transmission line, load data etc.) are given in Table III [10]. From Table III, it can be seen that the initial pitch angle ($\beta$) is 14.88°. It is calculated from equation (6) such that the output torque of the wind turbine is 0.6 per unit (at a base wind speed of 10 m/s). As the machine is of 0.5 MVA rating, the power coming out of the wind turbine will be $0.5 \times 0.6 = 0.3$ MW which is 30% of the total load demand.

### IV. PERFORMANCE ANALYSIS OF WIND/DIESEL SYSTEM

Using the above model, comprehensive simulation studies are carried out to observe the performance of the wind/diesel system. Simulations have been carried out using PSCAD/EMTDC software. A wind turbine’s power output depends on the wind speed, which is quite unpredictable. The objective here is to see the system behavior under both steady state wind regime and transient conditions such as change in wind speed (i.e., gust).

The complete PSCAD/EMTDC simulated system is shown in Figs. 2 and 3. In Fig. 2, the diesel generator system is shown while in Fig. 3; the wind turbine system is shown. As mentioned earlier, the MOD-2 wind turbine generator model has been adapted for the simulation. The wind source model, the diesel generator and the load model are also indicated in the figures. The wind turbine and diesel generator have been connected to the load through Y-Y, 13.8/9 kV transformers. The pitch angle controller is also shown separately in Fig. 3 [7]. The pitch angle dynamics are enabled at 5s through signal CNT. The synchronous machine runs in ‘constant speed’ mode at 1.5s (S2M).

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*Fig. 2. PSCAD/EMTDC simulated wind/diesel hybrid system showing the diesel generator.*
Fig. 3. PSCAD/EMTDC simulated wind/diesel hybrid system showing the wind turbine.

Fig. 4. Output real/reactive power and terminal voltages (in per unit) waveforms for diesel and wind at constant wind speed of 10 m/s.

A. Case 1 – Steady State

This situation occurs when there is no change in the wind speed (constant wind speed). The various real and reactive powers are shown in Fig. 4 for a constant wind speed of 10 m/s.

The induction machine is started at a constant speed (1.00127 per unit) which is slightly higher than the rated speed so as to generate power instead of absorbing power. This is only for the purpose of initialization. At 1 secs, the operation is switched to torque mode, which is being controlled by the wind turbine. At speed 10m/s, the power output from the induction generator (Pw) is 0.3 MW. The diesel power output is also constant since there is no variation in the wind power output. Therefore, in this case, the diesel generator provides the power (Pd) to the load which is 0.7 MW. P is the total power going into the fixed load. The terminal voltages are also shown in Fig. 4. It should be noted that per unit values of powers are shown in Fig. 4 with base value as 1 MVA.

The generators speeds (Wd & Ww) and pitch angle (Beta) variations are shown in Fig. 5. It can be seen that the generator speeds are constant around 1.0 per unit. The pitch angle settles at 14.9° which is around its initial value. This value is same as derived from equation (6) required to produce the wind turbine torque, Tmw, of 0.6 per unit or 0.3 MW. This is evident from Fig. 5.
By its nature, the wind speed is stochastic (uncontrolled) and it varies with the resource. For a typical wind site, the variation of wind speed over a period of time is shown in Fig. 6. It can be seen that the wind speed is never constant even for a small interval of time. However, we like our power very constant and controlled. Now, we shall study the system performance when there is a slight variation in the wind speed.

B. Case 2 – Wind Variation

With the system operating in the steady state, the system is subjected to a change at 10 s in which the wind speed is increased to 12 m/s from its nominal value of 10 m/s. The wind speed retains its nominal value after 50 s i.e., at 60 s as shown in Fig. 7.

The system response is shown in Figs. 8 & 9. It can be seen from Fig. 8 that due to the increase in the wind speed, the diesel generator power decreases momentarily while wind turbine power increases. However, these powers settle down to their pre-disturbance values of 0.7 pu and 0.3 pu respectively. The same behavior can be seen at 60 s when the wind speed changes to its original value. This is due to the pitch angle control of the wind turbine. The pitch angle (Beta) variation is shown in Fig. 9. In order to accommodate more wind, the pitch angle increases and attains a new steady state value of about 19.1°. The reverse transients can be seen at 60 s when the wind speed decreases to 10 m/s.

The requirement for the diesel generator system should be a simple control alternative. The pitch angle control method described above does regulate the power, but does not make use of the higher power capacity from the wind generator for higher wind speeds. It is possible to design a complex control system in which the pitch angle is changed dynamically to increase power during high wind speeds, but this involves a more complex algorithm.

In order to simplify the controller, we have investigated the system keeping the pitch angle, \( \beta \) constant at its nominal value of 14.9°. This simplifies the controller, but as will be shown, also allows the wind generator power to track the wind speed. The power output waveforms are shown in Fig. 10. When there is a variation in the wind speed, there is an increase in the wind power resulting in a decrease in the diesel generator power output so as to match the load. It can be seen from Fig. 10 that the diesel power is tracking the wind speed perfectly. The diesel and wind output powers are 0.47 pu and 0.53 pu respectively. Hence, there is a diesel fuel saving of about 33%. 

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Fig. 6. A typical wind speed data for a wind location.

Fig. 7. Wind speed changes at 10 s and 60 s.

Fig. 8. Corresponding diesel and wind power output waveforms and terminal voltages.

Fig. 9. The generator speed and pitch angle variations.

Fig. 10. Power output waveforms for Case 2 – Wind Variation.
Typically, a diesel generator has to be operated with at least 40% of the load. The terminal voltages remain constant throughout the process. And the governor of the diesel generator is controlling the frequency perfectly.

C. Case 3 – Sudden Wind Gust

In this situation, a wind gust is experienced. The wind speed is suddenly increased from a constant value of 10 m/s to a higher value of 12 m/s. Figure 11 shows the output power waveforms of wind and diesel generator. It is clearly shown in Fig. 11 that when there is a wind gust, the diesel and wind generator share powers among them in order to supply the load. Hence the load is not affected by the wind gust at all and the total power delivered to the load remains constant.

V. CONCLUSIONS

The paper explores the modeling and performance of wind-diesel hybrid power system for an isolated location with the aid of the PSCAD/EMTDC software package. A wind turbine’s power output depends on the wind speed, which is quite unpredictable. The objective here was to investigate the behavior of the wind/diesel hybrid power system under wind speed changes, which can be observed in the simulation results. It is shown that in every situation, the wind turbine and the diesel generator supply power in order to meet the power demand. The system is operating under wind gusts satisfactorily. From an energy-production point of view, it is desirable to have as much wind energy production as possible in order to save fuel consumption of the diesel engines.

The integration of the models presented here will provide a general tool for the accurate assessment of the power system stability and reliability of wind/diesel hybrid power systems.