Islanding Effects in Distributed Generation with Probability Analysis

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Abstract—A modeled distribution system is enhanced with distributed generation and islanding capacity. Probability analysis for renewable resources is explained and detailed. Different operating conditions are simulated, and the methodology of probability analysis is used to interpret the results. The usefulness of this method is explored, and the relevance of the simulated results is presented.


INTRODUCTION

The increasing interest in renewable resources has led to their becoming an important part of the modern electrical grid. Along with great potential, they also present challenges to incorporation, as does any new technology. Unlike conventional generation, renewable resources are predicted to be more decentralized across the grid. This can lead to a phenomenon known as islanding, where a small part of the interconnected grid can isolate and support itself through the use of its own generation [1]. To practically implement this, the resources must themselves be understood, which is difficult given the stochastic nature of renewables. With the mathematical tools of probability analysis, the uncertainty of renewables can begin to be evaluated and minimized. Simulations of the systems incorporating distributed generation can then be understood in light of these analyses.

A. Formulation of Technical Problem

In constructing this analysis, there are two distinct problems to be addressed when dealing with renewable resources: 1) the incorporation of these resources into the grid in terms of technologically determined operating effects, and 2) the economical dispatch (or commitment) of these resources.

The first problem to solve is the operating effects created by incorporating these resources into the grid. Three primary differences distinguishing this modeled distribution system from the typical system is the inclusion of doubly-fed induction generators (DFIGs) for the wind generation, inverters for the solar panels, and switching capability for the island.

B. Formulation of Commitment Problem

The second problem to be addressed is the uncertainty introduced into the operation of the grid from the stochastic nature of renewable resources. Unlike conventional generation which can be adjusted as needed, renewable resources are completely dependent on an unknown output [2].

To address this issue, the solution method of using probability analysis has gained traction in the study of renewables [3-7]. Using probability analysis as a tool, past information of a geographical region’s resources can be modeled to provide predictions of future performance. The challenge is then to determine which probability models perform the best with the different resources, and how they can be applied to specific situations.

DEVELOPMENT OF SYSTEM MODEL

To accurately understand the effects on operation from the renewable distributed generation, a realistic system model is required for the analysis.

A. Location Selection

A critical aspect of distributed generation that limits it more than conventional generation is location intensiveness. In the continental United States, many areas have the potential for either wind generation or solar generation, but not both. For this study, a moderately populated area with the potential for wind and solar generation was found in the coastal region of South Carolina. Several endeavors in wind power generation have begun in this area. As part of the southeastern area of the country, it also receives a moderate amount of solar irradiance.

B. System Topology

The system topology is a segmented model of a realistic distribution system with the upper segment powered solely by a substation, and the lower segment containing distributed
generation, and is adapted from previous research [8]. The
islanded portion contains 6 MW of load, and three different
sources of potential power generation in the forms of a wind
farm, a solar farm, and conventional backup generation. As
the islanded system is at the end of one radial line of buses, it
is capable of being connected to the grid or of being self-

C. Wind Generation

In modeling the renewable resources, wind generation was
given the largest role in power generation, with normal output
providing enough power to sustain the island. Since wind
generation has a typical capacity rate of roughly forty percent,
the total amount of wind generation in the island has a
nominal power output of 12 MW, which with the capacity
factor gives a typical output of 4.8 MW. This realization can
be accomplished by utilizing eight 1.5 MW wind turbines.
Just as important as the sizing of the resource is the profile
used in modeling; in this case, wind speed is recorded hourly
from the coastal Carolina region from January to December of
2009.

D. Solar Generation

The solar distributed generation is only a fraction of that of
the wind power, and by itself is incapable of providing
generation for the island. It is designed based on the 10:1 ratio
that has been used with hybrid systems, which has 10 MW of
wind generation per 1 MW of solar generation. However, this
is enough generation to aid with peak shaving within the
system, and for providing system support [9]. Nominaly, the
solar generation will have 1.2 MW of output, which is 20% of
the system load, but is enough to complement the
conventional backup generation. As with the wind generation,
the solar profile data is for 2009 recorded hourly from the
National Solar Radiation Database.

E. Conventional Backup Generation

The last source is the conventional backup generation. Since
the renewable resources provide the primary source of
generation for the islanded system, the power that can be
generated by the conventional backup is 5 MW. This requires
that there be at least a small amount of renewable generation
present to provide enough generation to make islanding a
viable option.

F. Load Dynamics

A final component that is relevant for a system changing in
generation is that of the load changing over time. Wind
generation is at a peak during the night, but the load is at a
minimum; however, without consideration of load change,
incomplete conclusions may be drawn from the analysis [10].
Therefore, the load is a 6 MW peak, but the load profile is
broken into six four-hour segments per day, with the average
load for each segment being determined by the load profile
consistent with the region used for the renewable resources.

MATHEMATICAL MODELING OF THE RENEWABLE RESOURCES

Much study has been conducted to research appropriate
mathematical models for renewable resources. The critical
element is the use of probabilistic models, or probability
density functions (pdfs), which can model the renewable
generation based on historical data [11]. For this research,
models for wind and solar resources will be utilized that can
express how much of the resource is present and how much of
that resource translates into power output.

A. Wind Resource Modeling

For wind modeling, the pdf that has been most developed is
the Weibull function, which can be mathematically described
in the following formula:

\[ f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \]  

(1)

where \( v \) is the wind velocity, and \( k \) and \( c \) are the shape
and scaling factors of the pdf, respectively. The shape factor, \( k \),
sets how the pdf will appear, either as a Gaussian-type
function centering around the mean wind speed, or an
exponentially-decreasing function beginning near zero. It is
calculated as

\[ k = \left(\frac{\sigma}{\mu}\right)^{-1.066} \]  

(2)

where \( \sigma \) is the standard deviation of the wind speed, and \( \mu \)
is the mean wind speed. The scale factor \( c \) determines, along
with the shape factor, the density of the Weibull function. This
is calculated by

\[ c = \frac{\mu}{\Gamma(1+\frac{1}{k})} \]  

(3)

where \( \Gamma \) is the gamma function, which calculates a modified
factorial of its argument. If the integral of the pdf is taken, a
simpler equation to compute probability can be found, which
is the cumulative distribution function, or cdf. For the Weibull
function, this can be expressed as

\[ F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \]  

(4)

As formulated in [12], the probability of the output being in a
certain range can be expressed as

\[ P = F(b) - F(a) \]  

(5)

where \( b \) is greater than \( a \).

B. Solar Resource Modeling

In previous studies, to model the output of solar generation,
several more stages needed to be developed. The first step was
to create a pdf for the clearness index, which is a measure of
the atmospheric conditions which let solar radiation through
to the earth’s surface. This is determined by the formula

\[ P(k_t) = C \ast \frac{(k_{tu} - k)}{k_{tu}} \ast \exp(\lambda \ast k_t) \]  

(6)

where \( k_t \) is the hourly clearness index, and \( C \) and \( \lambda \) are
determined by the maximum and mean of the clearness index,
\( (k_{ma}) \) and \( (k_{mn}) \), respectively. The formula for the variable \( C \) is

\[ C = \frac{\lambda^2 k_{tu}}{\exp(\lambda k_{tu}) - \lambda} \]  

(7)

and the formula for \( \lambda \) is

\[ \lambda = \frac{2\gamma - 17.159\exp(-1.311\gamma) - 1062\exp(-5.042\gamma)}{k_{tu}} \]  

(8)

The variable that relates these two functions to the pdf for the
clearness index is \( \gamma \), where

\[ \gamma = \frac{k_{tu}}{k_{tu} - k_{mn}} \]  

(9)
With this information, the solar irradiance on any tilted surface can be found using the function

\[ I_p = \left[ R_0 + \frac{1 + \cos \beta}{2} \right] k \cdot I_t \]  

(10)

This brings together several new variables, namely \( R_0 \), \( \beta \), \( k \), and \( I_t \). \( R_0 \) is the ratio of a beam of radiation on a tilted surface to that of a horizontal surface. The variable \( k \) is the fraction of radiation that is diffused on the horizontal plane, \( \beta \) is the reflectance of the ground, and \( I_t \) can be calculated from the formula

\[ I_t = I_p \cdot k_t \]  

(11)

In order to obtain the cdf of the solar irradiance function, the pdf must be integrated using integration by parts. By using this method, the cdf that emerges is

\[ cdf (k_t) = \frac{\mu}{\lambda} \int \left[ \left( \frac{\lambda}{\lambda + 1} \right) + \frac{\lambda}{\lambda + 1} \right] e^{\lambda k_t} \]  

(12)

where \( c \) is the constant of integration. Since the integral of all pdfs is by definition 1, setting the cdf equal to this yields a value of

\[ c = -\frac{\mu}{\lambda} \left( 1 + \frac{1}{\lambda + 1} \right) \]  

(13)

However, this means of calculating the solar irradiance has several inadequacies. Primarily, the clearness index does not reflect the difference in the natural amount of solar irradiance from the sun’s position relative to the earth’s surface based on the time of day. Additionally, the equations used to extrapolate the solar irradiance from this measure require additional variables, which are difficult to measure and obtain. A better way to calculate for the solar irradiance is to use the direct measure of radiation, and process it as a Gaussian (or normal) distribution. Thus, the pdf for solar radiation is represented as

\[ f(\text{solar}) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{(x-\mu)^2}{2\sigma^2} \right) \]  

(14)

where \( \mu \) is the mean of the solar irradiance, and \( \sigma \) is the standard deviation. As the normal distribution cannot be integrated deterministically, it is integrated using numerical methods to provide the probability for a given range.

C. Wind Power Modeling

After the pdfs and cdfs of renewable resources are developed, the models can then be adapted for the power outputs of the distributed generation. First, for the wind resources, the power output can be developed as

\[ P_v(v) = \begin{cases} 
0, & 0 \leq v \leq v_{ci} \\
\frac{P_{rated}}{v_{vi}} \cdot v_{co}, & v_{co} \leq v < v_r \\
\frac{P_{rated}}{v_{vi}} \cdot v_r, & v_r \leq v < v_{co} \\
0, & v_{co} \leq v 
\end{cases} \]  

(15)

This sets four different operating zones for wind generation, essentially its different output states. The first zone is defined for zero wind speed to the turbine’s rated cut-in velocity, where it begins to operate. The second zone has a variable output of power, as it increases as the velocity moves from the cut-in speed to its rated speed. After the turbine reaches rated speed, the power output remains constant up to the turbine’s cut-off wind velocity. Above this velocity, the turbine shuts down for purposes of self-protection and system stability.

D. Solar Power Modeling

For solar power output modeling, there is no analogous transformation of the cut-in and cut-off speeds; instead the power output is directly based on the solar irradiance. Therefore, the power output can be taken directly as the probability of differing amounts of solar irradiance relative to maximum output.

DIFFERENT OPERATIONAL STATES OF THE SYSTEM

Since transient analysis focuses primarily on short time frames that make the probabilistic models unnecessary, their importance is found in determining the operating states of the system. In this study, there will be five different operating states for the system which deal with the health of the system and the contributing mix of renewable resources.

A. Unhealthy

For an unhealthy system, the output power of the wind or solar distributed generation combined with the conventional backup is not enough to maintain the load. Since this is an underpowered situation that can result in blackouts, the switching operations to bring the system online or loads offline should be analyzed. Since the island contains 6 MW of load, and the backup generation provides 5 MW of output, if the renewable generation falls below 1 MW of output, the load cannot be fully supported.

B. Healthy with Wind Generation

In this zone, the power generated by both the wind and backup generation matches the load. In this state, the output from the wind resource must be between the limits of 1 and 6 MW, which is the range where the DG and backup generation can cooperatively meet the load. In this case, the solar generation is considered a non-factor, and is disconnected from the island.

C. Healthy State with all Generation

For this scenario, the power collectively generated by the solar, wind, and backup generation matches the load. Thus, the output from the renewable resources must again be between the limits of 1 and 6 MW.

D. Self-sufficient State with Wind

This operating state is when the wind resource is providing enough generation to fully power the island, and the backup generation can be kept at a minimum simply to provide the reactive power needed by the DFIG. Again, the solar resource is considered inconsequential, and therefore is disconnected.

E. Self-sufficient State with all Resources

Finally, this state is when the wind and solar resources are providing enough generation to fully power the island, and again the backup generation can be kept at a minimum simply to provide the reactive power needed by the DFIG.

PARAMETERS OF ANALYSIS

It is important to define what the parameters of the study are, as the area of operating analysis is quite broad. The next sections outline the parameters that have been used for the analysis.
A. Duration of Analysis

Often in renewable resource analyses the focus is to study how the renewables change with respect to time, but the time frames for this analysis will be much shorter, approximately 0.15 seconds (roughly 10 cycles). This means that the output of the distributed generation can be assumed to be static for the study period. These time frames will then give snapshots of the different operating points of the system, and the transients that can be expected in each state [13].

B. Specific Buses to be Studied

As the island is the focus of the study, the voltage and current of each bus in the island will be analyzed. Additionally, the voltage, current, and power output of each resource will also be carefully studied for transients. The only non-island bus that will be considered is the bus that connects the island to the system, which is the bus that would experience the most pronounced effects from tripping the island both online and offline.

C. Types of Operations to be Studied

The types of operations that will be studied are mostly switching operations. These can occur because of faults or operator intentional line tripping [14]. Therefore, several different scenarios will be presented, which include both faults (outside of the island), and normal-state switching operations.

CASE STUDY

The case study for this analysis is the compilation of the modeled distribution system and the data for the renewable resources and load. The system has been modeled in PSCAD previously by Saraf, using the appropriate DFIG model for the wind generation, and photovoltaic array and inverters for the solar generation. The probability analysis has been developed in a Matlab environment, where the different scenarios were programmed and the different scenarios were analyzed and plotted. Included here is the schematic of the system that has been developed for the research.

Figure 1: Modeled Distribution System

![Figure 1: Modeled Distribution System](image)

As for the contribution of the solar generation to the grid, it is stable when modeled as consistent irradiance affected by randomized cloud cover. The on-peak performance of the solar profile is displayed in Figure 2.

Figure 2: Plots of Solar Probability Functions

![Figure 2: Plots of Solar Probability Functions](image)

Fig. 2. This set of plots demonstrates the difference in the amount of solar irradiance at 4 PM across the seasons.

B. Simulation Results

From the simulations, it is seen that the effects from the distributed generation are not severe when a switching operation is carried out on the system. In fact, the most important result is that the working conditions of the renewable resources must be compatible in the steady state. In

### Table 1: Off-Peak Wind Generation (4 AM)

<table>
<thead>
<tr>
<th>Season</th>
<th>Probability of Full Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>56.24%</td>
</tr>
<tr>
<td>Summer</td>
<td>29.5%</td>
</tr>
<tr>
<td>Autumn</td>
<td>41.11%</td>
</tr>
<tr>
<td>Winter</td>
<td>50.76%</td>
</tr>
</tbody>
</table>

### Table 2: On-Peak Wind Generation (4 PM)

<table>
<thead>
<tr>
<th>Season</th>
<th>Probability of Full Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>38.06%</td>
</tr>
<tr>
<td>Summer</td>
<td>3.48%</td>
</tr>
<tr>
<td>Autumn</td>
<td>21.59%</td>
</tr>
<tr>
<td>Winter</td>
<td>40.91%</td>
</tr>
</tbody>
</table>

### RESULTS

The results from the analysis can be broken into two distinct fields: the probability analysis and the simulations.

A. Probability Analysis

From the results generated over the data sets of wind and solar resources, several interesting details emerge. The most important aspect about wind generation is its inability to meet peak demands, as the wind has a tendency to diminish as temperatures increase. This is demonstrated in the following tables, which are the ability of the wind to meet load demands on-peak and off-peak over the different seasons.
the transient effects that must be watched for, the most common effect is the increase in voltage at the islanding buses, which is due from having the generation nearby, instead of being transmitted through multiple lines which create loss and voltage depression.

CONCLUSIONS

There are several conclusions that can be drawn from this analysis which may be counter to typical intuition with regards to renewable resources. First, although wind is more plentiful at night than in the day, the effects of less wind are most severe in the summer, where at peak load it is inadequate to meet load. Second, with distributed generation, although it is more costly to keep potential generation as backup in a system, this could be mitigated in part by improving both the MAIFI and SAIFI of a system. It is also an important first step in creating a self-healing grid, which would increase both the economics and operational efficiency of the modern grid.

An additional takeaway is that since the renewable generation is greatest at night when the load is lowest, with the current lack of storage potential, it may be more economical to find the point of generation using probability analysis where wind could primarily be a supplement to the conventional generation. This would have the combined advantage of lower initial costs and less severe transients.

FUTURE RESEARCH

The next step of this research is to expand the simulations to unbalanced loads. Unbalanced loads produce neutral current which introduces an asymmetrical current into the distribution system [15]. In a typical distribution system, the likelihood of having a truly balanced situation is small. Therefore, investigating the situation thoroughly requires introducing unbalanced loads into the system, and observing the changes in the simulations.

REFERENCES