Impact of Transmission on Resource Adequacy in Systems with Wind and Solar Power

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Impact of Transmission on Resource Adequacy in Systems with Wind and Solar Power

Eduardo Ibanez, Member, IEEE, and Michael Milligan, Senior Member, IEEE

Abstract—Variable generation is on track to become a significant contributor to electric power systems worldwide. Thus, it is important to analyze the effect that renewables will have on the reliability of systems. In this paper we present a new tool being implemented at the National Renewable Energy Laboratory, which allows the inclusion of variable generation in the power system resource adequacy. The tool is used to quantify a first estimate of the potential contribution of transmission to reliability in highly interconnected systems and an example is provided using the Western Interconnection footprint.

Index Terms—Power transmission, power systems reliability, probability, solar energy, wind energy.

I. INTRODUCTION

The increasing amount of electrical load served by variable generation (VG), such as wind and solar energy, in the United States and many other countries has stimulated an interesting line of research to better quantify the capacity value of these resources. Methods applied traditionally to thermal units based on their average outage rates do not apply to VG because of their uncertain and non-dispatchable nature. The North American Electric Reliability Corporation’s (NERC’s) Integration of Variable Generation Task Force (IVGTF) recently released a report that highlighted the need to develop and benchmark metrics that reasonably and fairly calculate the capacity value of solar and wind power [1]. As the fraction of generation coming from VG becomes more relevant, their estimated capacity value will have an impact on system planning [2].

In this paper, we provide a method to include VG in traditional probabilistic-based adequacy methods. This method has been implemented in the Renewable Energy Probabilistic Resource Assessment tool (REPRA). Through an example based on the U.S. Western Interconnection (WI), this method will be applied to assess a first order approach of the effect that transmission can have in system adequacy. The results are significant enough to encourage further investigation, which would provide a better estimate of the contribution of transmission and allow a comprehensive analysis of the trade-offs between the addition of new transmission and new generation.

The remainder of the paper is organized as follows:

Section II introduces the concept of effective load carrying capability; Section III describes the REPRA tool used in this study; Section IV provides a numerical example that applies this methodology to the Western Interconnection; and, finally, Section V concludes and provides future steps.

II. EFFECTIVE LOAD CARRYING CAPABILITY

Generation system adequacy is the portion of electrical systems reliability that ensures that available capacity is sufficient to meet expected system demand within an acceptable risk threshold [3] at some future date. The metrics most commonly used to assess system adequacy revolve around probabilistic methods based the loss of load probability (LOLP). The loss of load expectation (LOLE) is a measurement of the expected days in a year that could face a generation shortfall. Similarly, the loss of load hours (LOLH) measures the expected number of hours in a year with insufficient generation.

The literature review in [4] and more recent examples in [1], [5] present the effective load carrying capability (ELCC) as an emerging suitable metric to evaluate the effect of VG. Given a reliability target, ELCC is defined for a system as the maximum load that could be served by the system while meeting said reliability target. We also can define the ELCC for a generation unit as the increase in the system ELCC when that unit is added to the system. Fig. 1 shows a graphical representation of this definition. The red horizontal line represents the reliability target of 1 day in 10 years, which is a common target used in industry. The blue line represents the reliability curve for the units already in the system, which has an ELCC of 10 GW. When a new generation unit is added the reliability curve shifts to the right. The horizontal difference between the systems curves, 400 MW, represents the new unit’s ELCC.

These calculations can be used to estimate the beneficial contribution to system adequacy from a transmission layout. Consider the different areas that are connected by said transmission layout. We could calculate the system ELCC for the resources in each area, essentially isolating them from each other. Since it is highly unlikely that the balance of resources and load is evenly distributed along the entire footprint, the transmission system can facilitate the transfer of extra generation capacity to the most problematic areas. Thus, the combination of the individual areas’ ELCC will be smaller than that of the entire footprint. The different between these...
metrics is the estimated adequacy contribution from the transmission system. The upper bound of this contribution can be found by comparing the individual areas to a copper sheet model, where perfect transmission is assumed between any two points in the system.

This methodology was used in NREL’s Eastern Wind Integration Study (EWITS) [6], which found that the existing grid transmission system in the Eastern Interconnection provides between 1,200 and 8,500 MW of tie benefits, depending on the load profiles used.

This simple representation of region connectivity allows us to evaluate the potential of performing a more detailed analysis with proper transmission representation. In reality, transmission capacity is a finite and probabilistic value. Transmission lines, like conventional generators, should be represented with a forced outage rate and a maximum capacity. We envision incorporating these capabilities into the REPRA tool, although analytical examples available in the literature are limited to two or three interconnected areas [3], [7]. Alternative methodologies include the use of Monte Carlo simulations, e.g., in GE’s Multi-Area Reliability Simulations (MARS) program [8].

### III. THE REPRA TOOL

The Renewable Energy Probabilistic Resource Adequacy tool (REPRA) is being developed at NREL to better understand how different types of renewable generation, which are usually non-dispatchable sources of power, can contribute to a power systems adequacy, from a reliability point of view.

At the core of the model resides a fast convolution algorithm that combines the probability distribution of the traditional generators. These are represented by a finite number of states. The most simple case is whether the unit is available or not, with a probability that it is not equal to the Effective Forced Outage Rate (EFOR).

Once the convolution of the traditional units [3] has been performed, the result is a capacity outage probability table, which indicates the LOLP for all levels of load the system can serve. For instance, Table I shows the result when considering six 50 MW units with an EFOR of 8%. The third row shows that the probability of an outage of 100 MW is 0.0688, which is equivalent to the probability of any two units being out of service. Similarly, the cumulative probability of an outage exceeding 100 MW is 0.0773; alternatively, one can interpret this cumulative probability as the LOLP associated with a 200 MW load level.

### TABLE I

<table>
<thead>
<tr>
<th>MW-OUT</th>
<th>MW-IN</th>
<th>Prob</th>
<th>LOLP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>300</td>
<td>0.6064</td>
<td>1.0000</td>
</tr>
<tr>
<td>50</td>
<td>250</td>
<td>0.3164</td>
<td>0.3936</td>
</tr>
<tr>
<td>100</td>
<td>200</td>
<td>0.0688</td>
<td>0.0773</td>
</tr>
<tr>
<td>150</td>
<td>150</td>
<td>0.0080</td>
<td>0.0085</td>
</tr>
<tr>
<td>200</td>
<td>100</td>
<td>5.20E-04</td>
<td>5.38E-04</td>
</tr>
<tr>
<td>250</td>
<td>50</td>
<td>1.81E-05</td>
<td>1.84E-05</td>
</tr>
<tr>
<td>300</td>
<td>0</td>
<td>2.62E-07</td>
<td>2.62E-07</td>
</tr>
</tbody>
</table>

Variable generation can be convolved with the capacity outage probability table in a similar fashion. The main difference is the determination of the probability distribution used in the convolution. Unlike traditional generators, VG production is limited by available resources such as wind speed or solar irradiance, which are governed by weather patterns. To preserve this variation, we make use of a sliding window technique [9] for all hours of the year. Figure 2 shows a graphical representation of a sliding window, which includes the current and adjacent hours. The width is predetermined and, in this case, it includes a total of five hours. Power outputs in the window are then given equal probability and sorted, providing the necessary probability distribution that will be included in an equivalent outage table (Table II). This table would then be convolved with the results in Table I to obtain the total system outage table (Table III). This table was truncated for LOLP values below 0.001.

### FIG. 2

Example of sliding window for wind power generation.

### TABLE II

<table>
<thead>
<tr>
<th>MW-OUT</th>
<th>MW-IN</th>
<th>Prob</th>
<th>LOLP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>90</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>20</td>
<td>80</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

REPRA allows the study of resource adequacy for different levels of geographic aggregation. This will contribute to a better understanding of the contribution of VG and also, as in this case, to better determine the benefits of a more interconnected system.
TABLE III
EXAMPLE OF CAPACITY OUTAGE PROBABILITY TABLE

<table>
<thead>
<tr>
<th>MW-OUT</th>
<th>MW-IN</th>
<th>Probability</th>
<th>LOLP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>400</td>
<td>0.243</td>
<td>1.000</td>
</tr>
<tr>
<td>10</td>
<td>390</td>
<td>0.243</td>
<td>0.757</td>
</tr>
<tr>
<td>20</td>
<td>380</td>
<td>0.121</td>
<td>0.515</td>
</tr>
<tr>
<td>50</td>
<td>350</td>
<td>0.127</td>
<td>0.394</td>
</tr>
<tr>
<td>60</td>
<td>340</td>
<td>0.127</td>
<td>0.267</td>
</tr>
<tr>
<td>70</td>
<td>330</td>
<td>0.0633</td>
<td>0.141</td>
</tr>
<tr>
<td>100</td>
<td>300</td>
<td>0.0275</td>
<td>0.077</td>
</tr>
<tr>
<td>110</td>
<td>290</td>
<td>0.0275</td>
<td>0.050</td>
</tr>
<tr>
<td>120</td>
<td>280</td>
<td>0.0138</td>
<td>0.022</td>
</tr>
<tr>
<td>150</td>
<td>250</td>
<td>0.0032</td>
<td>0.008</td>
</tr>
<tr>
<td>160</td>
<td>240</td>
<td>0.0032</td>
<td>0.005</td>
</tr>
<tr>
<td>170</td>
<td>230</td>
<td>0.0016</td>
<td>0.002</td>
</tr>
</tbody>
</table>

IV. NUMERICAL EXAMPLE

A. Data description

In this section, we apply the reliability tool introduced in the previous section to the Western Electricity Coordinating Council (WECC) footprint. The representation of the generation fleet is based on the upcoming Phase 2 of NREL’s Western Wind and Solar Study (WWSIS) [10]. This data is consistent with other studies performed by the WECC’s Transmission Expansion Planning Policy Committee (TEPPC) [11].

Table IV contains the list of Balancing Area Authorities (BAAs) that were considered in this example. BAAs were grouped in seven subregions, following the suggested zones in [12], with the only difference being that the Southern California subregion includes the Comisión Federal de Electricidad (CFE). Figure 3 presents a map of the different BAAs and the subregions they belong too, which are differentiated by different shades. In this example WAUW is merged into NWMT due to the small size of the former.

![Fig. 3. WECC Balancing Authority Areas and subregions.](image)

B. Results

The methods described in the previous sections were applied to the Western Interconnection footprint. Table V...
summarizes the main characteristics of the interconnection and its different subregions. The data includes the coincident load peak by region, along with the number of thermal and hydro units (conventional) and the capacity they represent, along with installed wind and solar capacity. The last column includes the resulting LOLE when the regions are analyzed by themselves, which is smaller than the usual 1 day in 10 years for the entire interconnection and most subregions. The Basin region and Southern California routinely import energy from other areas, which is consistent with the resulting high LOLE values.

The relative increase in peak load that could be served is very similar whether or not VG has been factored in: 33% for perfect interconnection transmission and 14% for infinite intrasubregional transmission. Additionally, we can examine the contribution of VG to the system adequacy by calculating the differences between the same aggregation levels with and without renewables. The results are displayed in Table VIII and correspond to the ELCC for the combined wind and solar power present in the system, and their average capacity value. Since these values increase with the level of aggregation, we can conclude that transmission also has a boosting effect on the contribution of VG to system adequacy.

The small regions VI need to be properly combined to be able to compare interconnection-wide results for all three aggregation levels. For instance, the load time series for each subregion is scaled using the appropriate factor. The sum of these load series is then used to find the new coincident interconnection-wide peak that can be served without violating the minimum LOLE for each subregion. The same process is performed starting with the BAA data and summarized in Table VII. The increase column shows the additional peak load that can be served when higher levels of aggregation are compared to the isolated BAA case. According to these results, perfect transmission between BAAs in the WI would allow the system to supply an additional 60.3 GW of peak load when VG is factored in. Half of that extra load could be served if we only considered perfect transmission within each subregion.

**TABLE VII**

<table>
<thead>
<tr>
<th>Region</th>
<th>VG</th>
<th>Peak load (GW)</th>
<th>Increase (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercon.</td>
<td>Yes</td>
<td>244.0</td>
<td>60.3 (33%)</td>
</tr>
<tr>
<td>Subregion</td>
<td>Yes</td>
<td>209.4</td>
<td>25.7 (14%)</td>
</tr>
<tr>
<td>BAAs</td>
<td>Yes</td>
<td>183.7</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE VIII**

<table>
<thead>
<tr>
<th>Region</th>
<th>VG ELCC (GW)</th>
<th>VG Capacity Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercon.</td>
<td>12.4</td>
<td>28.2</td>
</tr>
<tr>
<td>Subregion</td>
<td>10.1</td>
<td>23.0</td>
</tr>
<tr>
<td>BAAs</td>
<td>8.4</td>
<td>19.1</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

The methodology presented here is promising in quantifying the beneficial contribution of transmission to electric system adequacy. To gain a better understanding of this contribution this approach needs to be applied to other cases, including alternative footprints, historical time series data, and penetration levels of renewable generation.

The numerical example in this paper analyzes the contribution that perfect transmission has in the adequacy of a system. The results indicate that this contribution is significant. Furthermore, additional transmission enhances the capacity value of variable generation.

The promising results suggest that further work should be done to extend the methodology so that it is possible to enforce actual transmission constraints and force outage rates, as opposed to the copper-sheet analysis used in this paper. The result of this work will produce a more accurate estimation of the value of transmission in terms of resource adequacy.

VI. REFERENCES


VII. BIOGRAPHIES

Eduardo Ibanez (StM’08, M’11) received in the Diploma degree in Industrial Engineering from Universidad Pública de Navarra, Pamplona, Spain. He graduated from Iowa State University, Ames, IA with a Ph.D. degree in Electrical Engineering and a M.Sc. degree in Statistics. In May 2011, he joined the grid integration team at the National Renewable Energy Laboratory, Golden, CO, USA. His research interests include studying high levels of renewable energy penetration, transmission planning, and the integration of energy and transportation systems.

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