Utility Benefits of Using the Time Frame Capacity Factor Reliability Model

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This paper was presented at the 2018 IEEE PES Transmission and Distribution Conference and Exposition, Denver, Colorado, April 16–19, 2018, and can be accessed at: https://doi.org/10.1109/TDC.2018.8440382.

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***Abstract*—The time frame capacity factor (TFCF) model is a novel method used to determine the reliability of a power system with integrated renewable energy sources. The only information that this model needs is the capacity factor of a unit over the course of a year (TFCF). The TFCF reliability model can be further developed to simplify a microgrid using overall output power and capacity factor data. In such an environment, the large power grid is simplified considerably, and unknown parameters are kept to a minimum. There are several factors that motivate utilities to model a whole microgrid with a single source. This paper discusses the advantages of the TFCF reliability model for utilities.**

***Index Terms*—Capacity factor, microgrids, reliability assessment, renewable energy.**

I. INTRODUCTION

Renewable energy sources (RESs) have become a significant percentage of power generation in the U.S. However, they are variable and nondispatchable [1]. The operating schedules of such energy plants are largely dictated by ambient conditions. This is particularly true for wind and photovoltaic (PV) solar energy resources, which are the most rapidly expanding renewable resources. In the U.S., wind is expected to grow from 1.3 percent of the total supply in 2008 to 20 percent by 2030. These resources cannot be dispatched in the same way as conventional power generating units [2].

Wind power is volatile because of its low capacity factors, which are much lower than conventional units [1]. Wind power forecasting errors also present reliability estimation and planning problems [3]. Forecasting errors can occur more than 25 percent of the time depending on the ambient forecast timespan and forecasting methodology [2]. Solar is the most profuse source of energy. The solar energy reaching the surface of the earth over a year is significantly higher than the current worldwide power generated by fossil fuel. The variability of solar energy resources is very much impacted by climate and sunlight availability, causing the output of these resources to be extremely intermittent. This intermittency is noticeable not only each day, but also over the course of a year. The capacity factors for PV energy are typically 10 to 20 percent [1]. To overcome this problem, Monte Carlo simulation can be used as an easy-to-implement approach to simulating RES integration. Its use is detailed in [4], [5], [6], and [7]. The key problem with Monte Carlo simulation is that it needs a large amount of data sets that are mostly not available to the public. In [7], the solar irradiance is stochastically modeled using the clearness index, which is described as the quotient of the irradiance on a flat level and the extraterrestrial solar irradiance. Reference [6] applies a method that decomposes the hourly global irradiation on the horizontal earth's surface into diffuse, beam, and reflected components. For the wind energy, the simulated wind speed [7] and Weibull distribution function [4] [5] are used to calculate the power output.

The concept and formulation of the time frame capacity factor-based (TFCF-based) reliability model is presented in [8]. The capacity factor of RESs is used in a novel and composite transmission generation reliability model to measure the reliability of power systems based on the minimum load shedding. To improve the accuracy of the calculation, the overall time is subdivided into several time frames. Each time frame has its own TFCF. The model is best suited for isolated microgrids with RESs. The key advantages of the TFCF model are its simplicity, minimal running time, and data availability while covering low-probability scenarios.

Reference [9] proposes a TFCF-based reliability model for a grid-connected microgrid. The whole microgrid is modeled as a single, compact source with a combined capacity factor. Thus, to evaluate the reliability of the bulk power grid, each microgrid can be modeled simply as a source that interacts with the main grid. This saves time in large-scale studies and minimizes the dependency on analyzing detailed information about the components of a microgrid.

This paper discusses the advantages of the TFCF reliability model for utilities, which can have certain motivations for simplifying microgrids in reliability and planning studies. The advantages of this modeling make it a good fit for utilities looking to minimize uncertainties and get data from customers while calculating the reliability of the whole grid.

II. MOTIVATIONS

Microgrids are usually designed to work in both islanded and grid-connected modes. Thus, microgrids are connected to the bulk power system in a bus at the known points of common coupling (PCCs). From the utility standpoint, a microgrid can be as small as a home with an installed PV panel or as large as a private sector power plant (i.e., a geothermal unit) in the range of megawatts. Figure 1 shows an example of a power system with three interconnected microgrids (MG1, MG2, and MG3). Each can include RESs, storage units, lines, and loads.

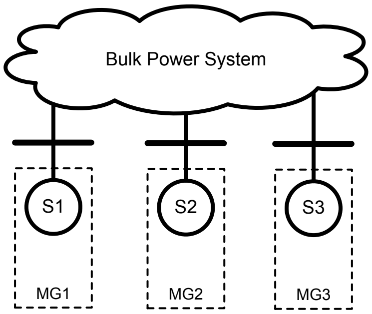

Figure 1. Grid-connected microgrids

Each microgrid is a small-scale power system and is composed of several elements such as RESs, internal loads, and storage units. MG1 is detailed in Figure 2 and consists of three buses, each with their own solar PV cell, storage unit, wind energy, and load. Lines connect the buses to each other. The batteries are charged with the unused capacity of the energy resources. To perform numerical studies, some arbitrary values are assumed. Detailed information about the components of MG1 is listed in [9]. In grid-connected mode, the utility feeder is connected to Bus 1.

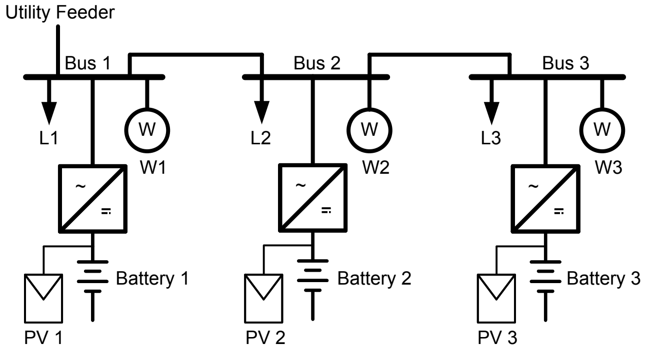

Figure 2. Schematic diagram of microgrid MG1 [9]

There are several issues that motivate utilities to choose a simplified microgrid model for reliability and planning studies. Some of these issues are discussed in the following subsections.

A. *Unknown Data*

Some data that a utility needs to consider for a microgrid when performing system studies are not accessible. The design specifications of wind turbines and solar PV panels are strictly concealed from the public, and historical data only exists in areas that have previously employed wind or PV generators [10].

Other parameters are not concealed, but sometimes unknown or inaccurate data make simulation and study results uncertain. This is the result of change over time, such as aging, maintenance, or the installation of new equipment with different specifications. Parameters such as inverter efficiency, cupper power loss, and voltage drop are generally in this category.

The output generation of resources, on the other hand, is among the accessible data for each unit. Thus, the capacity factor, which is simply defined as a unit's output divided by its maximum capacity, is readily accessible. The ease of access to the capacity factor largely contributes to its use in reliability evaluation.

B. *RES Intermittency*

Even though all of the design specifications of RESs are known, predicting the output power is still impossible. Fluctuation is always a part of RES power generation. Wind and solar energies in nature are known, nondispatchable intermittent resources. The generation of each unit depends on several stochastic parameters, such as ambient conditions, and also exhibits considerable change between maximum and minimum output.

In other words, the utility must model each RES with an average capacity and a standard deviation. The larger the standard deviation, the higher the uncertainty in the calculation.

However, in contrast to each individual unit, entire microgrid units exhibit a lower standard deviation because of the following factors:

- Wind and solar units have almost opposite behavior. In the month that solar units generate maximum power, wind units are in minimum generation, and vice versa [11] [12].
- Microgrids usually have internal storage to smooth the power outputs. Storage units with higher energy capacity are able to generate power for a longer duration, and high-power capacity storage units can cancel out higher power deviation [13].

C. *Operation Uncertainty*

A utility cannot control the importation or exportation of power through a microgrid [14] [15]. Each microgrid behaves as an independent system [16]. A microgrid considers several parameters, such as hourly price and storage capacity, and decides to either import power from or export power to the network. This mostly depends on the RES generation. A microgrid can have several operational modes. Some of these modes are listed in [17].

D. Microgrid Control Modes

Utilities need to know the current control mode and state of the network. When a microgrid runs with automatic controls, the controller is continuously running or initiating commands. The controller unit continuously monitors the network, collects data, and sends commands when required [17]. Some controls are operator-initiated. If prerequisites are satisfied, the controller unit performs the sequence of operation (breaker switching) [17]. It is not feasible for utilities to include control modes in their modeling because the modes are automatically managed by digital controllers.

E. Network Complexity

Microgrids include components that present highly nonlinear behavior that conventional power systems do not experience. Power electronic equipment, such as ac/dc and dc/ac converters, can be found in microgrids and require complicated modeling. For example, current limiters impact the output current of power electronic devices [18]. In such cases, utilities prefer to avoid such modeling, at least for reliability and planning studies.

Moreover, replacing a microgrid with a single source significantly decreases the dimension of the grid by subtracting the number of microgrid components (e.g., RES units, lines, and loads). In that case, the single source data covers the contingency analysis of microgrid equipment. As a result, utilities can perform reliability studies and contingency analysis faster and more contingences can be studied.

F. Internal Loads

Each microgrid has several internal loads that are used for its own internal consumers. The subtraction of the generation and internal load shows the amount of power that a microgrid can sell back to the utility grid.

Load factor (γ_L) is a normalized value between zero and one that represents the maximum consumed load over the rated value of all existing loads. Chronological studies certify that the loads change over the course of a year. For example, microgrid load factors are shown in Figure 3. Utilities do not have access to the load factor of individual internal loads inside microgrids.

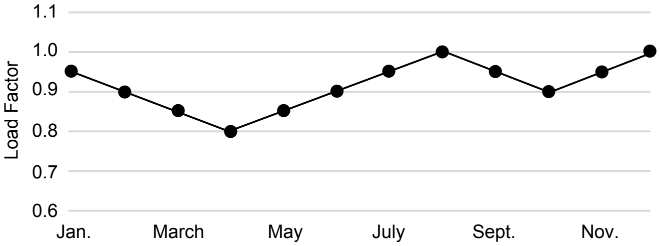

Figure 3. Load factors for the microgrid shown in Figure 2 [9]

G. Data Security

If a utility wants to include detailed microgrid data, a solid, continuous, and secure communications infrastructure between the utility and each microgrid is required. These data include characteristics of the microgrid and are different from all data points sent from large microgrids to supervisory control and data acquisition (SCADA) systems.

The TFCF reliability model minimizes the data exchange between microgrid operators and utilities. A continuous communications channel is not required because utilities only need two values from each microgrid—unit capacity (P_{Gen}) and TFCF. The maximum exported power over the last year and trends of output power are among the values utilities receive by default.

III. OVERALL CALCULATION PROCEDURE

The TFCF reliability model is designed for individual microgrids. This section details the calculations required to use the TFCF model.

A. Model Initialization

The microgrid is isolated from the entire power system at the PCC. The PCC is an infinite bus (a bus with a magnitude of 1 pu and phase angel reference of $\angle 0^{\circ}$) for the microgrid. A microgrid may be connected to several utility feeders because of reliability or operational constraints. In such cases, all PCCs are assumed to have the same voltage, which means all are electrically connected together.

A fictitious large load (L_{fict}) is assumed to be connected at the infinite bus (PCC), as shown in Figure 4. The value of L_{fict} must be larger than the sum of all installed generation capacities. Also, this load is assigned as the least critical load in the microgrid, which means that in case of load curtailment, it will be shed before any real internal load.

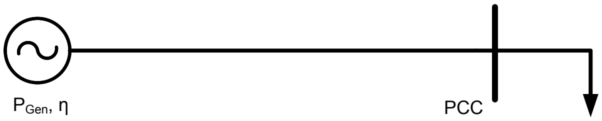

Figure 4. Microgrid connected to fictitious large load at PCC

For the microgrid shown in Figure 2, the PCC is Bus 1, so it is assumed as the infinite bus. Considering all internal loads, the large fictitious load may be considered in the range of several hundred kilowatts (e.g., L_{fict} = 1,000 kW).

B. Expected Energy Not Served

Several reliability indices exist [15], but among them, the expected energy not served (EENS) index is the one that considers both duration and the amount of unsupplied energy simultaneously. These data may be enough for the TFCF reliability model because the model requires only the amount of energy and time frame. In contrast, indices that only contain the duration of loss (such as loss of load probability [LOLP] and loss of load expectation [LOLE]) do not work for the model.

In the TFCF reliability model, all situations are modeled as a scenario, and the probability of that scenario is found based on the availability of each resource. The EENS is calculated for each scenario. The TFCF reliability model is compatible with the composite transmission and generation reliability approach [8], so contingencies of generation unit and transmission line outage can also be included in the model.

The EENS is an energy-oriented index that details the cumulative amount of energy not provided to customers [17]. EENS(TF_j) is the EENS index in the j^{th} time frame (TF), and it is calculated as shown in (1).

$$\mathrm{EENS}(\mathrm{TF}_j) = \sum_{i=1}^{N_s} \mathrm{Av}_{s,i} \bullet \mathrm{Av}_{w,i} \bullet \mathrm{Av}_{b,i} \bullet \mathrm{LC}_i \qquad \forall j = 1, \ldots N_{TF} \tag{1}$$

In (1), Ns is the number of scenarios considering the availability of RESs and storage units. The parameter *j* is an integer number between 1 and 12 indicating the number of the corresponding month (e.g., 1 for January, 2 for February, and so on). Parameters $Av_{s,i}$, $Av_{w,i}$, and $Av_{b,i}$ are, respectively, the availability of solar, wind, and storage units in scenario *i*. The average EENS is the weighted sum of the EENS values for all time frames, as shown in (2).

$$\mathrm{EENS} = \sum_{j=1}^{N_{TF}} \omega_j \bullet \mathrm{EENS}(\mathrm{TF}_j) \tag{2}$$

In (2), ω_j is the weighting factor of each time frame, and its value is based on the duration of that time frame. If a year is divided into equal time frames, the weighting factors for all time frames will be equal, as expressed in (3).

$$\omega_j = \frac{1}{N_{TF}} \tag{3}$$

Thus, (2) is simplified as shown in (4).

$$\mathrm{EENS} = \frac{1}{N_{TF}} \sum_{j=1}^{N_{TF}} \mathrm{EENS}(\mathrm{TF}_j) \tag{4}$$

$LC_{Min,j}$ and $LC_{Max,j}$ are found as shown in (5) and (6).

$$\mathrm{LC}_{Min,j} = P_L \bullet \gamma_{L,j} + L_{fict} - P_{Gen_{Max}} \tag{5}$$

$$\mathrm{LC}_{Max,j} = P_L \bullet \gamma_{L,j} + L_{fict} \tag{6}$$

$\gamma_{L,j}$ is the load factor for TF_j, L_{fict} is the large fictitious load, and $P_{Gen,max}$ is the maximum generated power in the microgrid that can be transferred to internal and fictitious load considering network constraints (e.g., the capacity of transmission lines, voltage drop, and reactive power limits) [8].

LC_{Max} is the sum of the internal loads (P_L) and the fictitious load (L_{fict}). When all sources are off, the internal load must be fed through the utility.

When the TFCF-based reliability model is run [8], for each time frame, EENS(TF_j), $LC_{Min,j}$, and $LC_{Max,j}$ are calculated for all months as shown in Figure 5.

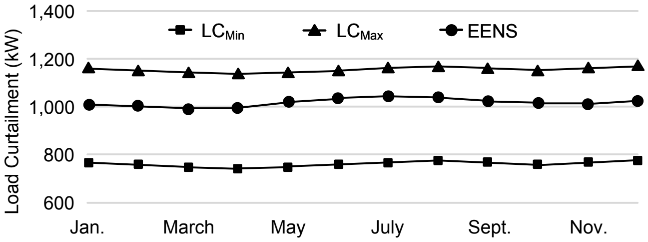

Figure 5. EENS and load curtailments for microgrid shown in Figure 2 [9]

C. *Equivalent Source Specification*

When EENS(TF_j) is determined in (2), the equivalent source in each time frame is found (see (7), (8), and (9)). A single source unit with the capacity factor η has an EENS value equal to (7).

$$\mathrm{EENS}(\mathrm{TF}_j) = \eta_j \bullet \mathrm{LC}_{Min,j} + (1-\eta_j) \bullet \mathrm{LC}_{Max,j} \tag{7}$$

If the EENS(TF_j) presented in (7) is equal to the general equation in (1), then η_j represents the overall TFCF [8]. In other words, the weighted sum of a multiple-state system, formulated in the right side of the equal sign in (8), is equal to the weighted sum of the two-state system, formulated in the left side of the equal sign in (8).

$$\eta \bullet \mathrm{LC}_{Min} + (1-\eta) \bullet \mathrm{LC}_{Max} = \sum_{i=1}^{N_s} \mathrm{Av}_{s,i} \bullet \mathrm{Av}_{w,i} \bullet \mathrm{Av}_{b,i} \bullet \mathrm{LC}_i \tag{8}$$

The generation capacity for each time frame is calculated in (9).

$$P_{Gen,j} = P_{Gen_{Max}} - P_L \bullet \gamma_{L,j} \tag{9}$$

$P_{Gen,j}$ is not necessarily the difference of all installed generations and all internal loads in the microgrid because other factors, such as transmission line capacity limits and storage capacities, affect this value.

From (5), (6), and (7), η_j is calculated in (10).

$$\eta_j = \frac{\mathrm{LC}_{Max,j} - \mathrm{EENS}(\mathrm{TF}_j)}{\mathrm{LC}_{Max,j} - \mathrm{LC}_{Min,j}} \tag{10}$$

According to (5) and (6), L_{fict} is canceled out from the $LC_{Max,j}$ – $LC_{Min,j}$ result in (10). Thus, $P_{Gen,j}$ and η_j are independent of the arbitrarily selected, fictitious large load.

The results presented in Figure 5 are further processed by (9), and for each time frame, the value of $P_{Gen,j}$ is found as shown in Figure 6.

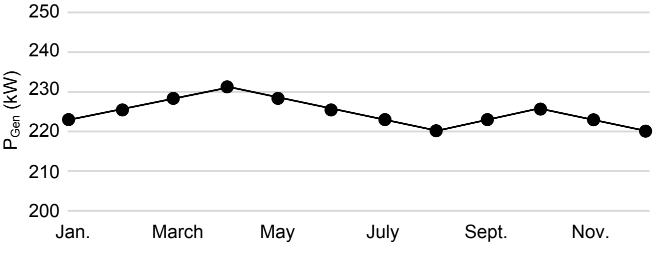

Figure 6. Equivalent output power for the microgrid shown in Figure 2

As shown in Figure 6, for all time frame values, $P_{Gen,j}$ may vary because of network constraints, seasonal load changes, and the different capacity factors of RESs that lead to different net generations exported to the utility. The values found in different time frames must be unified in the sense of the same output power, and the TFCF must be updated accordingly. Thus, P_{Gen} is calculated in (11).

$$P_{\mathrm{Gen}} = \mathrm{Max}(P_{\mathrm{Gen,j)}} \qquad \forall j = 1,...N_{\mathrm{TF}} \qquad (11)$$

The capacity factor for each time frame is updated in (12).

$$\eta_{\mathrm{j,New}} = \eta_{\mathrm{j}} \bullet \frac{P_{\mathrm{Gen,j}}}{P_{\mathrm{Gen}}} \qquad \forall j = 1,...N_{\mathrm{TF}} \qquad (12)$$

Equations (11) and (12) state that for all time frames, a common output power (P_{Gen}) is selected and the capacity factor is updated to keep the output power matching the output power calculated in (5).

Figure 7 certifies that the average TFCF has a narrower range, and also that maximum and minimum capacity factors are in March and July, respectively, which does not match those of wind and solar units individually.

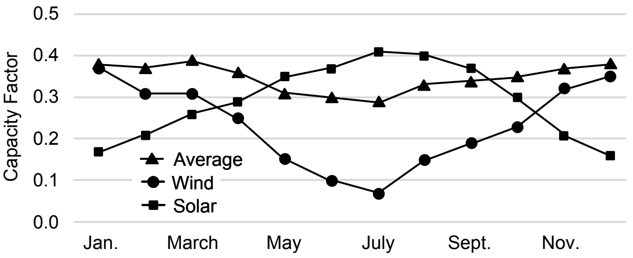

Figure 7. TFCF of wind and solar units vs. the whole microgrid

Because of the opposite behavior of wind and solar generation and the existence of storage units, the overall capacity factor has a narrower range of change. Despite the drastic change RESs exhibit during a year, utilities can expect more accurate numbers with lower deviation and uncertainty for a microgrid.

IV. CONCLUSION

A utility neither needs to know nor has access to detailed information regarding all of the components of a microgrid because the microgrid is operated by an autonomous control entity. Each microgrid has different operational modes and control strategies that are beyond the utility's control. There are several large loads that turn on or off when the local energy management system decides. Likewise, a utility cannot control when power is imported or exported through the microgrid. What a utility is interested in knowing for each microgrid is the TFCF over a period of time (i.e., one year). This is a combined TFCF taking into account all RESs. In such an environment, the large power grid is simplified considerably, and unknown parameters are kept to a minimum. The results in this paper indicate that microgrids have a more predictable capacity factor because of the narrower range shown in Figure 7.

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Previously presented at the 2018 IEEE PES Transmission and Distribution Conference and Exposition, Denver, CO, April 2018.