

DETERMINING THE SUFFICIENCY OF STANDARD PROTECTIVE RELAYING FOR ISLANDING PREVENTION IN GRID-CONNECTED PV SYSTEMS

M. Begovic, M. E. Ropp¹, A. Rohatgi, A. Pregelj

¹Corresponding author

School of Electrical and Computer Engineering

Georgia Institute of Technology

Atlanta, GA 30332-0250

Phone: (404) 894-0336

FAX: (404) 894-4832

E-mail: michael.ropp@ece.gatech.edu

ABSTRACT: Recently there has been a resurgence of concern about islanding of grid-connected photovoltaic (PV) systems. This condition occurs when the PV system continues to energize a section of the grid after that section has been isolated from the main utility voltage source. Generally, islanding is undesirable for a number of reasons, and it is therefore important that PV systems incorporate methods to prevent islanding. However, PV systems are in general already required to be equipped with standard protective relays, namely over/undervoltage relays (OVR/UVR) and over/underfrequency relays (OFR/UFR), which disconnect the PV system from the utility system in the event that either the magnitude or frequency of the PV system's terminal voltage deviates beyond certain thresholds. These relays will prevent islanding in the majority of cases. In fact, it has been argued that the probability of an islanding event that would not be detected by these relays is insignificant. The purpose of this paper is to investigate the probability of occurrence of the conditions which could lead to failure of the OVR/UVR and OFR/UFR to detect islanding using three methods, and thereby to determine whether the standard protective relays provide sufficient islanding protection.

Keywords: Islanding - 1: Probability - 2: Protective relays - 3

1. INTRODUCTION

Islanding occurs when a utility-interactive photovoltaic (UIPV) system continues to energize a section of the utility grid after that section has been disconnected from the main utility voltage source. It is generally considered undesirable for two reasons: 1) it poses a potential safety hazard to system repair personnel who may be unaware that the section is still being energized; 2) the PV system generally relies on the utility to provide its phase reference, and therefore a phase error between the PV system and utility voltage can develop while the PV system is islanding. If the utility attempts to reclose on the out-of-phase section of the grid, large surge currents could damage the PV system and the local load.

UIPV systems are usually required to have protective relaying which causes the PV system to disconnect itself from the utility system in the event that the voltage at the PV system's terminals (point of common coupling [POCC] with the utility system) becomes abnormal. According to the proposed new standard IEEE-P929 [1], over/underfrequency relays (OFR/UFR) must disconnect the PV system if the frequency of the POCC voltage goes beyond ± 0.5 Hz from nominal, and over/undervoltage relays (OVR/UVR) operate if the magnitude of the voltage goes outside 92% and 110% of the nominal POCC voltage. Because the magnitude and/or frequency of the POCC voltage will change after the utility is disconnected from the majority of PV-load combinations [2], these four "standard relays" in fact prevent islanding under most conditions. However, if the load and PV powers are sufficiently closely matched, and the load's resonant frequency lies sufficiently close to the nominal utility frequency, the

changes in voltage magnitude and frequency when islanding begins will fall within the trip thresholds, and the OFR/UFR/OVR/UVR will not operate. The range of loads meeting this description is referred to as the nondetection zone (NDZ) of the relays.

For some time, it has been a subject of debate as to whether it is in fact possible to see such loads in practice. Many have argued that the probability of encountering a load within the NDZ of the four standard relays is so small as to be of no concern, in spite of the fact that one study done in Japan found evidence to the contrary [3]. The purpose of this paper is to attempt to determine the probability of encountering a load which lies within the OFR/UFR/OVR/UVR NDZ using realistic conditions observed in the United States, a probability which will be referred to herein as the "NDZ probability". This analysis indicates that this probability can be high *under certain conditions*, and therefore additional islanding protection beyond the OFR/UFR/OVR/UVR is necessary.

2. PROCEDURE: DIRECT APPROACH

To represent the load, measured real and reactive power (P and Q) data from U.S. utility companies was used. Using measured load data allows confidence that the general behavior of the load in terms of such parameters as demand curve shape and power factor is in fact realistic; also, such data were readily available. The utility P and Q data were measured at the substation level (13.5-45 kV) and represent an aggregate load. The data sets were collected at 10 or 15 minute intervals and span at least one year. The utilities also supplied the locations at which the measurements were made and a general

description of the load composition (residential, commercial, industrial, and whether power factor correction capacitors [PFCCs] were employed on the feeder being monitored).

Next, the output of a PV system at the location of the measured data was simulated. In each case, the PV system was oriented due-south with latitude tilt. PV system simulations were carried out using the program PVGRID with meteorological data from the TMY2 database. PVGRID supplies hourly PV system power outputs. Linear interpolation was used to obtain sub-hourly values.

The conditions under which the OFR/UFR/OVR/UVR would not detect islanding were then expressed in terms of the available data. The OVR/UVR rely on a mismatch between PV and load real powers to detect islanding. A "match" between the real powers of load and PV exists when, if the load were transferred from utility power to PV power, the voltage at the POCC would not change sufficiently to trip the OVR/UVR. The criterion for a real power match was derived by assuming that the load could be modeled as a parallel RLC circuit and that all of the real power is dissipated in the resistive part. Given a real power measurement at time k , P_k , and assuming a (nominal) utility voltage V_0 , the value of the resistance at time k is

$$R_k = V_0^2 P_k^{-1} \quad (1)$$

If the utility were suddenly disconnected, assuming that the PV system acts as a current source, the new PV system terminal voltage is determined by R_k and the PV system power at time k , $P_{PV,k}$ according to

$$V_k = \sqrt{R_k P_{PV,k}} \quad (2)$$

We can substitute (1) into (2) to obtain

$$V_k V_0^{-1} = \sqrt{P_{PV,k} P_k^{-1}} \quad (3)$$

Therefore, using the OVR/UVR threshold values [1], if

$$(0.92)^2 \leq (P_{PV,k} P_k^{-1}) \leq (1.1)^2 \quad (4)$$

is satisfied, there is a match between PV and load powers and the load lies within the OVR/UVR NDZ.

The situation for the OFR/UFR is more complicated. The OFR/UFR NDZ includes loads whose resonant frequencies lie within the relays' frequency trip thresholds [2]. However, without a knowledge of the L and C of the load, we cannot determine the load's resonant frequency. We do know the load displacement power factor (dpf), which is

$$dpf_k = P_k (P_k^2 + Q_k^2)^{-1/2} \quad (5)$$

We can also express the load dpf in terms of the R and either the L or C of the load:

$$dpf_k = \cos \left\{ \tan^{-1} \left[R_k C_k \omega_{res,k}^2 \omega_0^{-1} (\omega_0^2 \omega_{res,k}^2 - 1) \right] \right\} \quad (6)$$

Figure 1 shows the results of Equation (6) for $\omega_{res,k}$ corresponding to the frequency trip thresholds of the OFR/UFR as a function of C and for several values of R. Figure 1 is thus a map of the OFR/UFR NDZ in dpf-C space. Each curve is actually a pair of curves lying nearly atop one another, one corresponding to loads with resonant frequencies of 59.5 Hz (leading dpf at 60 Hz), the other corresponding to loads with resonant frequencies of 60.5 Hz (lagging dpf at 60 Hz). The region above each pair of curves (at higher

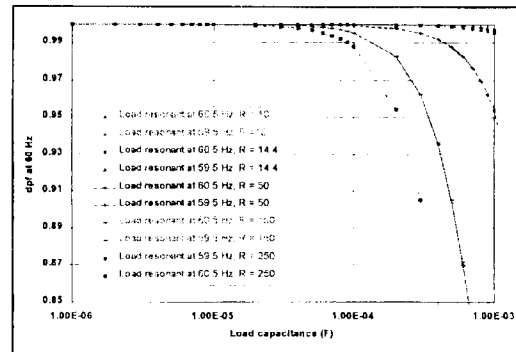


Figure 1. 60-Hz dpf of loads whose resonant frequencies correspond to the OFR/UFR trip limits of ± 0.5 Hz.

dpf values) is the NDZ of the OFR/UFR. The range of C values on the x-axis is physically reasonable; values of C in the hundreds of μF range are possible when cable capacitances, dynamic load characteristics, and PFCCs are taken into account [4]. Values of C smaller than the 1 μF value at the origin of the x-axis are certainly possible as well, but the values of L required to resonate with these would be in the single-digit henries range, which is unlikely in practice.

Figure 1 and Equation (6) clearly show that dpf is not a unique function of resonant frequency. However, they do show that, if R and C are confined to a very narrow range (allowing L to vary), then a dpf threshold can be selected which approximates the boundary of the OFR/UFR NDZ. Therefore, the procedure which has been adopted here is to treat the dpf threshold as a parameter and determine the NDZ probability for several different values of the dpf threshold. A dpf threshold is set for the entire measurement period and compared against each dpf_k from Equation (5). If

$$dpf_k \geq dpf_{threshold} \quad (7)$$

is satisfied, the load is said to lie within the NDZ of the OFR/UFR at that time k. By repeating this procedure for dpf thresholds which span the practical range (that is, that correspond to the ranges of practical R and C), the maximum and minimum values of the NDZ probability of the OFR/UFR may be calculated. Note that the

conditions which yield the extreme dpf thresholds, and give the maximum (worst-case) and minimum (best-case) probabilities, may be unlikely in practice. We believe the most-likely range of resistances and capacitances to be 10-250 Ω and 10-100 μF respectively. Inserting into Equation (6) yields the most *likely* range of dpf criteria, between 0.988 and 0.9999998.

In this study, two different NDZ probabilities have been calculated. The first is the total NDZ probability during all daylight hours over the entire data measurement period. "Daylight hours" are defined as any hour in which the simulated PV system is producing nonzero power. Probabilities were calculated using a MATLAB program which compares the measured load data and modeled PV data point-by-point, checking at each point to see whether the criteria defined by Equations (4) and (6) are both satisfied. When they are, a counter is incremented, and after all data points have been checked the probability is computed as the total number of points at which the criteria are both met divided by the total number of points. This probability was calculated as a function of PV system size, normalized to the load's average real power demand.

However, the matching of PV and load powers can be modeled as a random process, meaning that the NDZ probability is not constant but varies as a function of time of day. To reflect this time-varying nature, we have also calculated the NDZ probability as a function of time of day (the "conditional NDZ probability"). This was done by limiting the data set to all the points which fall within a time interval and repeating the above-described procedure on this limited data set.

At this point, we must note that this study makes no assumptions about the stability of an island, or whether upon utility disconnection a transient may occur which would alter the system's behavior.

3 RESULTS

The total daylight-hours NDZ probabilities for three different data sets are shown in Figure 2, Figure 3, and Figure 4 as a function of the PV system size. The three data sets are:

- Data Set #1, from a small city, primarily residential, without PFCCs;
- Data Set #2, from a major metropolitan area, residential, with PFCCs;
- Data Set #3, from a rural area, primarily residential with large induction motors driving pumps and no PFCCs.

In each of these figures, four dpf thresholds have been used: the minimum load dpf for each data set, which gives the worst case; the two extremes of the most "likely" range of dpf thresholds (0.9999998 and 0.988); and the highest-possible dpf threshold (= 1.0), which is the best case. In all cases the NDZ probability is zero for PV systems whose power ratings are less than about 70% of the load's average real power demand, no matter what

dpf threshold is selected, because a real power match is never achieved. The minimum NDZ probabilities, corresponding to small values of C and R, are always near zero. Unfortunately, the maximum NDZ probabilities,

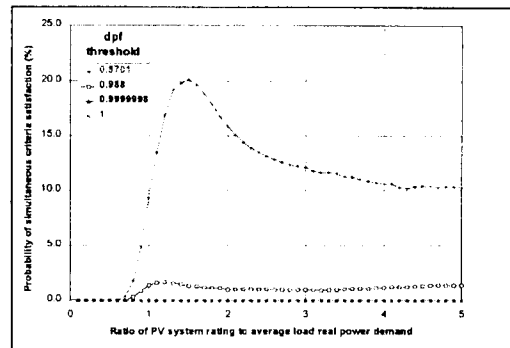


Figure 2. Total daylight-hours probability of simultaneous criteria satisfaction, Data Set #1.

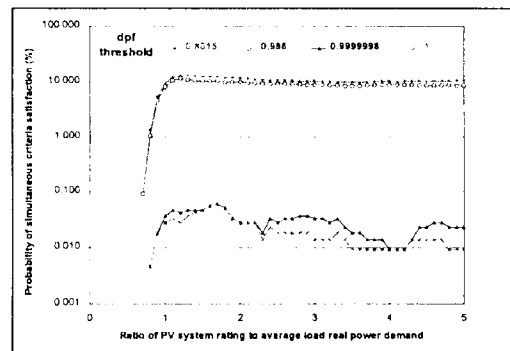


Figure 3. Total daylight-hours probability of simultaneous criteria satisfaction, Data Set #2. A log-linear scale was used so that the fact that the probability never reaches zero is visible.

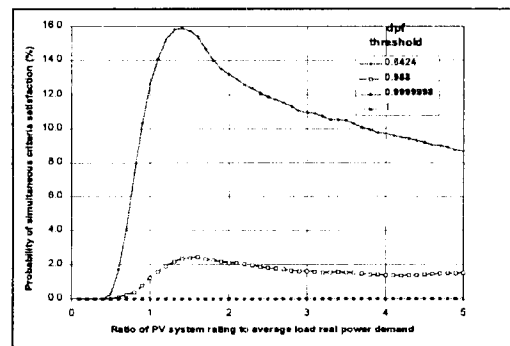


Figure 4. Total daylight-hours probability of simultaneous criteria satisfaction, Data Set #3.

corresponding to larger C and R, are significant, reaching over 20% in one case. The true probability will fall somewhere between these two extremes, but clearly it is possible for practical loads to fall within the NDZ of the four standard relays. Thus, in general, the OFR/UFR/OVR/UVR alone cannot guarantee that a PV system will not island.

The results of computing the probability as a function of time of day are shown in Figure 5, Figure 6 and Figure 7. For these calculations, in order to make the shape of the curves clear, a low value of dpf threshold (0.95) was used. These figures show that the probability of criteria satisfaction during daylight hours at certain times of day can be much larger than the total probability. Note also the behavior of the conditional probability as the PV system size is increased. For systems which are rated at ~100% of the load power demand, the probability peaks near midday as the PV system's power production reaches the load demand and real power matches become more likely. As the PV system size increases, this midday peak "splits" into two peaks, one moving to earlier times and one to later. This occurs because the larger PV system's real power matches the load's demand for a brief period early in the day, then exceeds it, making a real power match near noon less likely. The reverse happens near the end of the day.

4. PROCEDURE: ANALYTICAL MODEL

An approximate analytical solution to this problem is also possible. To obtain it, we define:

$$x^i = P_{PV} P_L^{-1}; y^i = P_L [P_L^2 + Q_L^2]^{-1/2} \quad (8)$$

where i ranges from 1 to the number of observations per day. If x^i and y^i are jointly normal random variables, then their joint density is given by an analytical function which is completely determined by five parameters, which are the expected values η , variances σ , and correlation coefficient r of x^i and y^i [5]:

$$f(x, y) = A \exp\left[-\frac{B}{2(1-r^2)}\right] \quad (9)$$

$$A = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-r^2}}$$

$$B = \frac{(x-\eta_x)^2}{\sigma_x^2} - 2r\frac{(x-\eta_x)(y-\eta_y)}{\sigma_x\sigma_y} + \frac{(y-\eta_y)^2}{\sigma_y^2}$$

According to the criteria defined previously, the NDZ will have the rectangular shape shown in Figure 8. The conditional NDZ probability then can be calculated by integrating the probability distribution over the NDZ:

$$P\{(x, y) \in NDZ\} = \iint_{NDZ} f(x, y) dx dy \quad (10)$$

The histograms for typical x^i and y^i are shown in Figure 9. The goodness of the normal fit is debatable;

however, as shown in Figure 10, applying this procedure to the data set to Data Set #1 for a dpf threshold of 0.95 leads to a result which is similar to that shown in Figure 5. Assuming a normal distribution appears not to have significantly affected the accuracy of the analysis.

5. PROCEDURE: MONTE CARLO METHOD

The results shown in Figure 5, Figure 6 and Figure 7 are somewhat noisy because of the limited number of data points. This effect can be largely eliminated by generating a synthetic data set with the correct statistical interrelationships but with many more data points. For each measured data set, we define random variables P_{PV}^i, P_{load}^i and Q_{load}^i ($i=1, \dots, n$), defined as the set of yearly values for P_{PV}, P_{load} and Q_{load} for a particular time of day. Histograms for one set

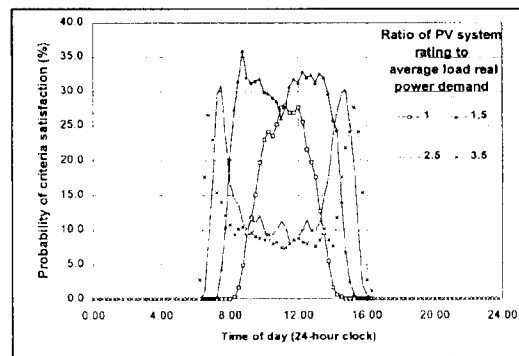


Figure 5. Probability of simultaneous criteria satisfaction as a function of time of day, Data Set #1. The dpf threshold was set at 0.95.

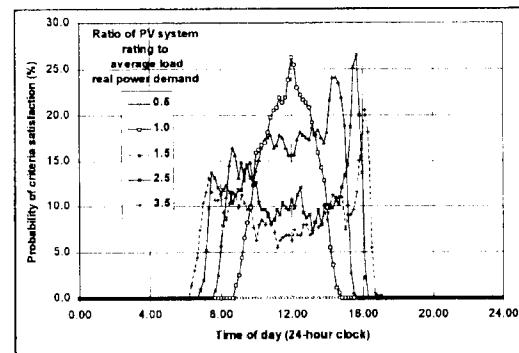


Figure 6. Probability of simultaneous criteria satisfaction as a function of time of day, Data Set #2. The dpf threshold was set at 0.95.

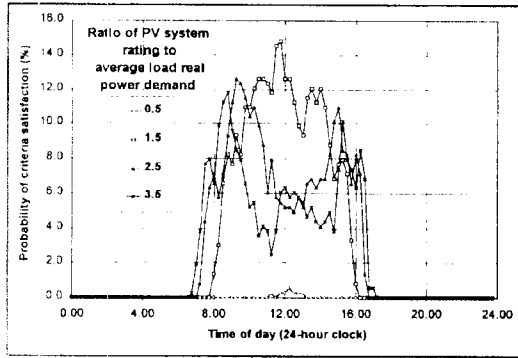


Figure 7. Probability of simultaneous criteria satisfaction as a function of time of day, Data Set #3. The dpf threshold was set at 0.95.

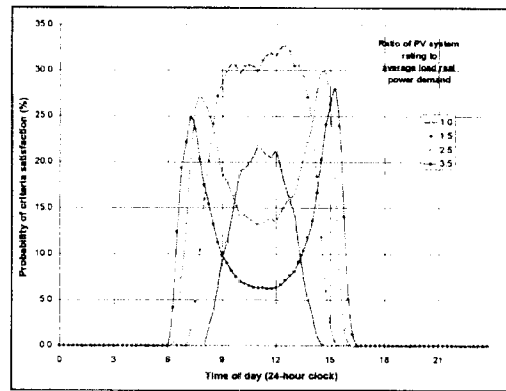


Figure 10. Conditional NDZ probability, Data Set #1. The dpf threshold was set at 0.95.

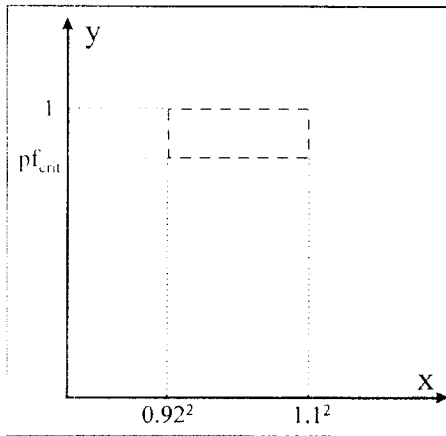


Figure 8. The nondetection zone (NDZ).

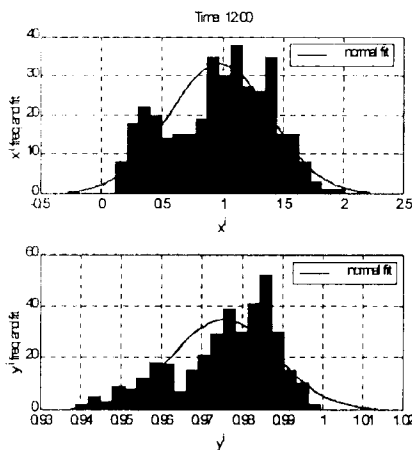


Figure 9. Normal fit of x^1 and y^1 ; data from Data Set #1. Ratio of PV system rating to average load real power demand is 1.5.

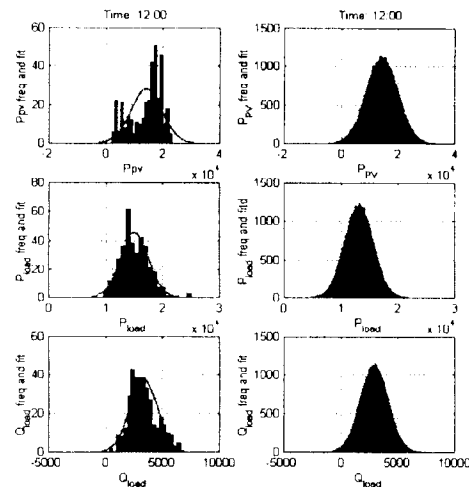


Figure 11. The RVs P_{pv} , P_{load} and Q_{load} (left) and RN sequences generated from them (right), Data Set #1. Ratio of PV system rating to average load real power demand is 1.5.

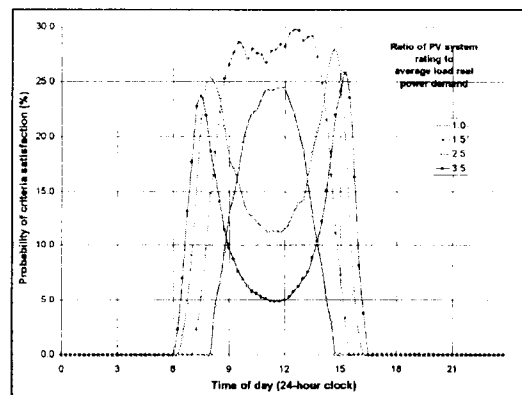


Figure 12. Conditional NDZ probability calculated using synthesized data based on Data Set #1. The dpf threshold = 0.95.

of P'_{PV} , P'_{load} and Q'_{load} are shown on the left side of Figure 11. If these three variables have a multivariate normal distribution, they are completely determined by their means vector $\mu = (\mu_{PV}, \mu_{load}, \mu_{Qload})$ and a covariance matrix Γ [6]. Therefore, by extracting the parameters μ and Γ from the measured data for P'_{PV} , P'_{load} and Q'_{load} , we can synthesize random number (RN) sequences of arbitrary length and use these sequences to calculate the conditional NDZ probability using the same procedure used previously, described in Section 2 of this paper. An example of the results of this process as applied to Data Set #1 and for a dpf threshold of 0.95 is shown in Figure 12. Again, the shape of the curve is the same as these in Figure 5 and Figure 10. Although again the goodness of the normal fit to the data is questionable, it appears to be accurate enough for purposes of this analysis.

6. CONCLUSIONS

We have presented the results of a systematic study to determine whether the OFR/UFR/OVR/UVR provide sufficient islanding protection. This study entailed a statistical study of measured aggregate load data from U.S. utilities compared with modeled PV system performance data at the same locations. The difficulties encountered in setting accurate failure criteria for the frequency relays were discussed. Finally, we have presented two sets of probability calculations, one showing the total probability of encountering a load within the NDZ of the OFR/UFR/OVR/UVR over the entire period of the measured data (the "NDZ probability"), and the other showing the probability of encountering a load within the OFR/UFR/OVR/UVR NDZ as a function of time of day (the "conditional NDZ probability"). The results of this study show that, under realistic conditions, it is possible to have loads which lie within the NDZ of the four standard relays. This indicates that the four relays cannot guarantee that a PV system will not island, and further protective measures are required for grid-connected PV systems.

It is important to note that this study does have limitations. The load has been represented by measured aggregate load data in order to realistically model the load shape and power factor. The results of this study should hold for all loads whose demand pattern and power factor behavior are represented adequately by this data. However, it must be restated that the NDZ probability can range from zero to over 20% depending on the value of dpf threshold used. This is in turn dependent on the values of R, L and C of the load. Clearly, more accurate (R,L,C) load data would enable a more conclusive study.

For example, if the ranges of R, L and C could be determined for a specific installation site, it would be possible to more accurately determine the NDZ probability for that site, and the appropriateness of additional protective measures would then be more clear. It must also be clearly stated that this study does NOT find the "probability of islanding", but rather the probability that, at any given time, the load lies within the NDZ of the OFR/UFR/OVR/UVR. This is not the same as the probability that a PV system actually will island, which is affected by the probability of the utility actually being disconnected from the PV system and the action of any additional islanding protection schemes, among other factors. However, the NDZ probabilities calculated here are important because they show that the OFR/UFR/OVR/UVR acting alone are not sufficient to guarantee the safety and integrity of people and property, and therefore additional islanding protection is needed for UIPV systems.

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