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# Reliability Assessment Of A Photovoltaic Distributed Generation System Using The Universal Generating Function

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**Abstract:** Due to the growing energy demand, projected to double in 20 years, and global warming, the latter being of vital importance since electricity generation currently causes 24% of greenhouse gas emissions, society modern is facing an unsustainable energy system. Therefore, the application of renewable distributed generation systems is growing rapidly in distribution systems, especially photovoltaic systems. Therefore, in this work it is proposed to carry out a model for the assessment of reliability in a Colombian rural distribution system when photovoltaic distributed generation systems are entered, using the technique of the universal generating function and comparing the results when conventional distributed generation is entered.

**Keywords:** photovoltaic generation, reliability assessment, universal generating function.

## I. INTRODUCTION

Due to climate change, many countries have established policies to encourage their energy industries to switch from using fossil fuel energy sources to renewable energy. Therefore, the connection of many Distributed Generation (DG) units in the Distribution systems (DS) is expected, the introduction of these systems affects the reliability of the DS.Therefore, the reliability assessment is a fundamental tool.

Said reliability theory is based on probabilistic methods for the reliability evaluation of the DS. According to reports in the literature, the methods could be divided into two categories, analytical methods [1]–[7]. And Monte Carlo simulation (SMC) [8], [9]. Within the analytical methods we find the technique of the universal generating function (UGF), which is widely used for the reliability assessment of multi-state systems (MSS) [8]-[9], the UGF approach is simple that provides a systematic method for the enumeration of system states that can replace complicated combinatorial algorithms. Furthermore, combined with simplification techniques, it is an effective tool, especially when it is desired to implement optimization procedures [16].

The rest of the document is organized as follows in section 2 the modeling of the system is performed, specifically in section 2.1 and 2.2 the stochastic model of a photovoltaic generation system and the stochastic model of the load are given respectively, in the section 2.3 introduces the universal generating function and in sections 2.4, 2.5, 2.6 and 2.7 the model of photovoltaic generation systems, conventional generation, distribution system and load respectively is made, with the technique of the universal generating function, in section 2.8 the model of the complete system is made and in section 2.9 the reliability evaluation indices to be used are introduced. In section 3 3 case studies are given and in section 4 the conclusions are presented.

## II. MODEL OF THE DISTRIBUTED PHOTOVOLTAIC GENERATION SYSTEM

### Stochastic model of photovoltaic generation

The output power of photovoltaic systems (PV) is not deterministic, this due to the intermittent nature of solar radiation, what has been said above raises the need for a stochastic model that captures the non-deterministic behavior and randomness of PV systems. The solar panel is the central element of the photovoltaic system; its output depends on several factors, among which the most dominant is the solar irradiance on the panel in kW / m ^ 2. BeingSthe area of the PV system and let $\mathrm{I(t)}$be the solar irradiance received at time t, then the output of the $\mathrm{P_{PV}}$of the PV system is [17]:

$$\mathrm{PPV} = \begin{cases} \frac{\eta_C}{K_C} * S * I(t)^2 & 0 < I(t) \leq K_C \\ \eta_C * S * I(t) & I(t) > K_C \end{cases} \quad (1)$$

Where $\eta_C$ is the conversion efficiency of the PV system including the inverters and a$K_C$ is a threshold, when the received irradiance is less than $K_C$, PPV has a second order relationship with $I(t)$,when the received irradiance is greater than$K_C$, PPV has a linear relationship with $I(t)$.

$$S = S_P * N_p \qquad (2)$$

Where $S_P$ is the area of a solar panel and $N_p$ is the number of solar panels.

Solar irradiance is mainly affected by solar altitude angle, clouds, temperature, and humidity. The variation of the solar altitude angle with time in a day can be determined by a definitive function, while the other variables are random as the weather changes.It can be considered that the received solar irradiance $I(t)$ is equal to a fundamental irradiance $Id(t)$determined by the solar altitude angle plus a random amount of attenuation $\Delta I(t)$product of the other variables, that is

$$I(t) = I_d(t) + \Delta I(t) \qquad (3)$$

Neglecting the influence of the change of seasons on the time of sunrise and sunset, $I_d(t)$can be considered a quadratic function, which is represented by

$$I_d(t) = \begin{cases} I_{max} * \left(-\frac{1}{36} * t^2 + \frac{2}{3} * t - 3\right) & 6 \le t < 18 \\ 0 & 0 \le t < 6; 18 \le t < 24 \end{cases} \qquad (4)$$

Where t is the time in a day, whose unit is the hour; $I_{max}$ is the maximum solar irradiance in a day, which is usually at 12 noon, that is, $I_{max} = I(12)$.

In a simplified way, it can be considered that $\Delta I$ (t) obeys the normal distribution. The normal distribution probability density function can be represented by the following function:

$$f(\Delta I) = \frac{1}{\sqrt{2\pi}} * e^{-\frac{\Delta I^2}{2*\sigma_I^2}} \qquad (5)$$

**Stochastic model of the load**

In practice, load values are generally recorded every hour over a specific time horizon (e.g. one year).To model the dynamic behavior of loads, many models have been proposed, in this work we consider the load duration curve model (LDC), as seen in figure 1, the LDC model classifies all chronological load values in descending order of magnitude and divide the ordered charge values into NL states and the i-th state includes$NL_i$, the probability of the i-th charge state is [8]:

$$P_i = \frac{NL_i}{8760} \qquad (6)$$

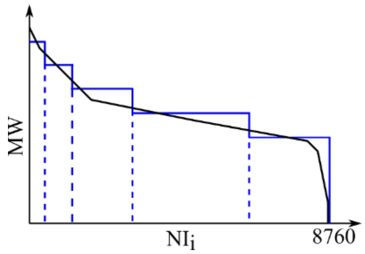

Figure 1. Multi-stage model of the load duration curve

**Universal generating function**

The universal generating function (UGF) technique allows finding the performance distribution of a multi-state system (MSS) based on the performance distributions of its elements by using algebraic procedures [16].

**Mathematical foundations**

First consider a discrete random X variable that can take on a finite number of possible values .The probability distribution of this variable can be represented by the finite vector$\mathbf{x} = (x_0, \dots, x_k)$ which consists of the possible values of X and the finite vector p which consists of the corresponding probabilities$p_i = \Pr\{X = x_i\}$. The assignment$x_i \rightarrow p_i$is usually called the probability mass function (pmf) [16].

Now consider n independent discrete random variables $X_1, \dots, X_n$and assume that each $X_i$variable has apmf repres ented for$\mathbf{x}_i, \mathbf{p}_i$vectors. To evaluate thepmfof an arbitrary function$f(X_1, \dots, X_n)$, we have to assess the$\mathbf{y}$of all possible values of this function and the vector$\mathbf{q}$ of the probabilities that the function takes these values.Each possible value of the functionfcorrespond to a combination of values of its arguments$X_1, \dots, X_n$. The total number of possible combinations is

$$K = \prod_{i=1}^{n}(k_i + 1) \quad (7)$$

Where$k_i + 1$is the number of different realizations of the random variable Xi. Since all n variables are statistically independent, the probability of each unique combination is equal to the product of the probabilities of that combination. The probability of the$j-$th combination of the variables can be obtainedas

$$q_j = \prod_{i=1}^{n} p_{ij_i} \quad (8)$$

And the corresponding value of the of the function can be obtained as

$$f_j = f(x_{1j_1}, \dots, x_{nj_n}) \quad (9)$$

Some different combinations can produce the same function values. All combinations are mutually exclusive. Therefore, the probability that the function takes on some value is equal to the sum of the probabilities of the combinations that produce this value. On the other hand, each of the random variables $X_i$ con $pmf(x_{i0},\ldots,x_{iki}),(p_{i0},\ldots,p_{iki})$, can be represented in polynomial form, applyingthe transformedz, as shown below:

$\sum_{j=0}^{k_i} p_{ij} * z^{x_{ij}}$ (10)

In a general way the transformed zthat represents thepmfof the arbitrary functionfcan be obtained by applying a general composition operator $\otimes_f$over the transformation representationzofpmfofnindependent variables:

$$\otimes_f \left(\sum_{j_i=0}^{k_i} p_{ij_i} * z^{x_{ij_i}}\right) = \sum_{j_1=0}^{k_1} \quad \sum_{j_2=0}^{k_2} \ldots \sum_{j_n=0}^{k_3} \left(\prod_{i=0}^{n} p_{ij_i} * z^{f(x_{ij_1},\ldots,x_{nj_n})}\right) \quad (11)$$

The technique based on the use of transformedzand composition operators $\otimes_f$is called UGF. In the context of this technique, the transformationzof a random variable for which the operator is defined$\otimes_f$is calledfunction $-$ u. We refer to thefunction $-$ uof theXivariable as$u_i(z)$and to thefunction $-$ uof functionf$(X_1,\ldots,X_n)$as$U(z)$.According to this notation

$$U(z) = \otimes_f (u_1(z), u_2(z), \ldots, u_n(z)) \quad (12)$$

Where $u_i(z)$ y $U(z)$ take the form of equations (10) y (11) respectively.

**Multi-state model of the photovoltaic generation**

The first step for multi-state modeling is to transform the continuous distribution of solar irradiance into a discrete distribution [18]. For this, Iis divided into $n_I$ states of equal size, being the probability of the j-th state:

$$Pr(I_j) = \int_{(j-1)*\Delta I}^{j*\Delta I} f(I)dI \quad (13)$$

Where$\Delta I = I_{max}/n_I$is the size of the step and$I_j$is the value of the solar irradiance in the j-th state

$$I_j = \frac{j*\Delta I + (j-1)*\Delta I}{2} \quad (14)$$

On the other hand, in solar generation, there are two different sources of randomness: one is the external solar irradiance and the other is the internal mechanical degradation of the elements that make up the system, we assume that they are independent of each other.

For solar irradiance, in the left part of figure 2, the state '0' represents that there is no power generation, the state $'n_I - 1'$represents the irradiance produces the maximum power output given that all solar panels are working. For mechanical degradation (failure / repair) states, for simplicity, we assume that each solar panel has only two states (working or in total failure), leading to a total of two states$n_{PF}$of the solar generator (it fails when none of its modules are working and works perfectly when all of its modules are working). In the right part of Figure 2, the state "0" represents the failure of a solar generator panel "$n_{PF} - 1$" represents when all the solar panels are working [18].

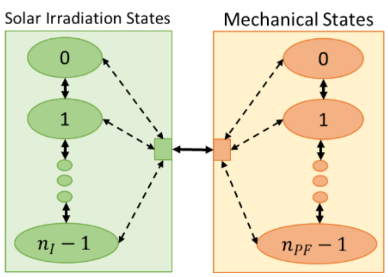


Figure 2. Solar irradiance states and mechanical states of solar generators.

Let's suppose that$G_i^I$and$G_i^{PF}$are the discrete random variables withpmf$(g_{i0}^I, g_{i1}^I, \dots, g_{in_I-1}^I), (p_{i0}^I, p_{i1}^I, p_{in_I-1}^I)$and$(g_{i0}^{PF}, g_{i1}^{PF}, \dots, g_{in_{PF}-1}^{PF}), (p_{i0}^{PF}, p_{i1}^{PF}, p_{in_{PF}-1}^{PF})$representing the states of solar irradiance and the mechanical condition, respectively, according to the equation 10 for solar irradiance, thefunction $-$ uthat links the probability of state i, $p_i^I$, with the value of the corresponding state denoted as $g_i^I$(that is, the output power of a single panel for the solar irradiance level i), is given by

$$u_I(z) = \sum_{i=0}^{n_1-1} p_i^I * z^{g_i^I} \qquad (15)$$

Similarly, the u-function of the mechanical condition is defined as:

$$u_{PF}^i(z) = \sum_{i=0}^{n_{PF}-1} p_i^{PF} * z^{g_i^{PF}} \qquad (16)$$

where$g_i^{PF}$ denotes the status value of$G^{PF}$(in the case of the solar generator, it is the number of solar panels in operation).

To represent the power output in a coherent way with equation (1), the operator given in equation (11), is established as a function of structure multiplication type of two random variables$G_1$and$G_2$, therefore equations (11) and (12) take the form

$$U(z) = u_1(z) \otimes_\times u_2(z) = \sum_{i=0}^{n_1-1} \sum_{j=0}^{n_2-1} p_i^1 \, p_j^2 z^{\varphi_\times(g_i^1, g_j^2)} \qquad (17)$$

With the random variables$G_i^I$ y $G_i^{PF}$, it is possible to obtainpmfof the output power of the solar generator$G^{PPV} = P(I_j, N_P)$, therefore applying equation (17) to the output power of the PV generator given in equation (1)thefunction $-$ uof the solar generator power output$G^{P_{PV}}$can be written as:

$$u_{PPV}(z) = u_I(z) \otimes_{\times} u_{PF}^{i}(z) = \sum_{i=0}^{n_1-1} \sum_{j=0}^{n_{PF}-1} p_i^I * p_j^{PF} * z^{g_i^I \times g_j^{PF}} = \sum_{i=0}^{n_{PPV}-1} p_i^{P_{PV}} z^{g_i^{PPV}} \quad (18)$$

where$n_{PPV} = n_I * n_{PF} - \delta_{PPV}$is the number of redundant states (that is, states with the same amount of power output). As previously mentioned, this allows states to be reduced.

**Multi-state model of the distributed conventional generation**

In conventional generation (MT), there is only one source of randomness, which is the internal mechanical degradation of the elements that make up the system, for practical purposes in modeling the mechanical degradation of the conventional system will be taken equal to the mechanical degradation of solar generation systems, modeled previously therefore the function $-$ u of the conventional generation model will be:

$$u_C(z) = \sum_{i=0}^{n_C-1} p_i^C * z^{g_i^C} \quad (19)$$

Where$C_i$is the output power of a conventional generator in state i.

**Multi-state model of the rural distribution system**

Distribution systems are complex systems with multiple components (lines, transformers, fuses, etc.) operating in series and parallel, in addition, these components can have multiplex operating states, therefore, carrying out the multi-state model of this system is beyond the scope of this work, taking into account that the objective of this work is to analyze the impact on the reliability of an unreliable rural distribution system, when they are entered into charging points distributed generation systems,consequently, the distribution system will be modeled as a two-state system, working and therefore delivering energy to the load or in failure with zero power supply to the load, the función $-$ uof the proposed distribution system is shown below

$$u_D(z) = \sum_{i=0}^{n_D-1} p_i^D * z^{g_i^D} \quad (20)$$

Where $D_i$ is the power delivered by the distribution system in state i.

**Multi-state of load model**

As mentioned above, the LDC load model will be used, which divides the load values into NL.Therefore the function − uof the multi-state load model would be:

$$U_L(z) = \sum_{i=0}^{NL-1} p_i^L * z^{g_i^L} \quad (21)$$

Where$L_i$is the energy consumption in state i of the load.

**Multi-state model of the complete generation system**

To establish the multi-state model of the distributed photovoltaic generation system, the following assumptions are made to combine the component models introduced above.

1. As shown in figure 3 all distributed generators are connected in parallel, because they share a common feeder (distribution line). The load profiles are represented by an LDC model.
2. For multiple solar generators, the energy sources (i.e. solar irradiance) are perfectly correlated, respectively. This assumption is reasonable for generators located in a geographically close area and can significantly reduce the number of states of the generators combined.

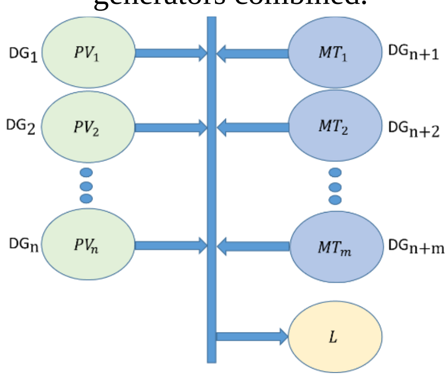


Figure 3. Simple model of the distributed generation system and load ($DG_1, \ldots, DG_{n+m}$are the nominal generation capacities of n PV units and m MT units, L is the load in a certain time).

3. For solar and conventional generators, the internal mechanical degradation / repair mechanism is mutually independent of each other. This is a common assumption in MSS reliability modeling.
4. As already mentioned above, it is assumed that the random process of failure / repair of the rural distribution system and the random processes of failure / internal mechanical repair of both solar generators and conventional generators, have only two states, fully working or total failure, therefore it can be modeled as a Markov process of stochastic transitions between the two states of operation and failed.

By assumptions (2) and (3), we obtain the function $-$ u of the combined solar generators as follows

$$\begin{aligned} u_{PPV}(z) &= u_{PPV}^{1} \otimes_{+} \dots \otimes_{+} u_{PPV}^{i} \otimes_{+} \dots \otimes_{+} u_{PPV}^{ms} \\ &= u_{I}(z) \otimes_{\times} \left[u_{PF}^{PPV_1}(z) \otimes_{+} \dots \otimes_{+} u_{PF}^{PPV_1}(z) \otimes_{+} \dots \otimes_{+} u_{PF}^{PPV_{ms}}(z)\right] \end{aligned} \quad (22)$$

where$u_{PPV}^{i}(z)$isfunction $-$ uof the i-thsolar generator, $u_I(z)$is thefunction $-$ u of solar irradiation for all the solar generators, $u_{PF}^{i}(z)$is thefunction $-$ uofmechanical state of the i-th solar generator, and$m_s$is the total number of solar generators.The operator UGF $\otimes_{+}$between two u-functionsis defined as $u(z) = u_1(z) \otimes_{+} u_1(z) = \sum_{i=0}^{n_1-1} \sum_{j=0}^{n_2-1} p_i^1 p_j^2 z^{\varphi_{+}(g_i^1, g_j^2)}$, where$\varphi_{+}(\cdot)$is the composition function that represents the relation $\varphi_{+}\left(g_i^1, g_j^2\right) = g_i^1 + g_j^2$.

The function $-$ uof all types of generators combined is:

$$U_G(z) = u_{PPV}(z) \otimes_{+} u_C(z) + u_D(z) = \sum_{i_{PPV}}^{n_{PPV}^{*}} \sum_{i_C}^{n_C-1} \sum_{i_D}^{n_D-1} (p_i^{P_{PV}} * p_i^{C} * p_i^{D} * z^{\varphi_{+}(g_i^{PPV}, g_i^{C}, g_i^{D})}) \quad (23)$$

where$n_{PPV}^{*} = n_I^{PPV} \cdot \prod_{i=1}^{ms} n_{PF}^{PPV_i} - \delta_{PPV}$ (where$n_I^{PPV}$ is the number of states of solar irradiation, $n_{PF}^{PPV_i}$is the number of the mechanic statesof the i-thsolar generator, and$\delta_{PPV}$is the number of redundant states) are the total numbers of states of the solar generators combined. By further reducing the number of terms in (22), the system's generation function $-$ utakes the form:

$$U_G(z) = \sum_{i=0}^{n_G-1} p_i^G z_{g_i}^G \quad (24)$$

where$n_G = n_S^{*} * n_C * n_D - \delta_G$is the total number of power states of the system generation and $\delta_G$is the number of redundant states.

Given assumption (1) above, the function $-$ u of the load model has the form of equation (21).

**Reliability assessment indices**

At steady state in the system there must be a balance between the total generation G and the load L. In case of failure in the distributed generation system, the load may exceed the available generation $(G < L)$. The fault condition can be represented by an LLF pressure drop function:

$\mathrm{LLF}(G,L) = 1(G < L) = \begin{cases} 1, & \text{if} G < L \\ 0, & \text{if} G \geq L \end{cases}$ (25)

Applying the composition operator $\otimes_{LLF}$over a system represented by thefunctions $-$ u$U_G$ (z) y$U_L$ (z)given in the equations (24) y (21) respectively the function $-$ u that represents the pmf of the LLF operator (G, L) is obtained:

$$U_{LLF}(z) = U_G(z) \otimes_{LLF} U_L(z) = \left(\sum_{j=1}^{n} p_j * z^{g_j}\right) \otimes_{LLF} \left(\sum_{i=1}^{NL-1} p_i^L * z^{g_i^L}\right)$$

$$= \sum_{j=1}^{n} \sum_{i=1}^{NL-1} p_j * p_i^L * z^{1(g_j, g_i^L)} \qquad (26)$$

The expected value of LLF is equal to the probability that LLF $= 1$, in other words, the probability that the generation system cannot supply the load. This index is generally known as LOLP (Loss of Load Probability), the LOLP can now be obtained as

$\mathrm{LOLP} = E(\mathrm{LLF}) = \sum_{j=1}^{n} \sum_{i=1}^{k} p_j * p_i^L * \mathrm{LLF}(g_j, g_i^L)$ (27)

Two common reliability assessment indices are Loss of Load Expectation (LOLE) and Expected Energy Not Supplied(EENS). The first is the expected period during which the load demand is greater than the available generation and can be represented as

$$\mathrm{LOLE} = E\left(\sum_{s=1}^{S} \frac{T}{S} * \mathrm{LLF}(G,L)\right) = \frac{T}{S} * S * E\big(\mathrm{LLF}(G,L)\big) = T * \mathrm{LOLP}$$

$= T \sum_{j=1}^{n} \sum_{i=1}^{k} p_j * p_i^L * \mathrm{LLF}(g_j, g_i^L)$(28)

Where T is the operating time and S is the number of equal intervals into which T is divided.

On the other hand, EENSes is the expectation of the energy that the system cannot supply and is given by:

$\mathrm{EENS} = T \sum_{j=1}^{n} \sum_{i=1}^{k} p_j * p_i^L * (g_i^L - g_j)\mathrm{LLF}(g_j, g_i^L)$ (29)

Where$g_i^L - g_j$is the energy that the system cannot supply in the period of time i.

## III. CASE STUDY

The load data of the case study is taken from the RBTS-BUS6 test system, bus 6 is used since it is a typical rural distribution network, specifically the load at load point 25 will be taken into account, which is a residential charging point with 79 customers and a peak and average load of 277.6 kW and 155.4 kW respectively, Figure 6 shows the modified distribution system, when the distributed generation system is entered, which will work in parallel together with the distribution system and will be able to supply 100% of the load in case of failure of this.

Figure 3 shows that all sources that deliver power are modeled as connected in a parallel logical structure, the output of which provides the power to meet load demand. As already mentioned, the rural distribution system is represented by a two-state MARKOV model: in operation and in failure.It is assumed that the rural distribution system is an unreliable distribution system, for the case of some regions of Colombia this statement is completely true [19], therefore the failure and repair rate will be assumed to be 0.027/year and 0.25/year, respectively. When solving the Markov model, the constant probabilities of the work and failure states are 0.9 and 0.1, respectively. Applying these values in the model given in section 2.6, The UGF model is then:

$$u_D(z) = 0.9 * z^{277.6} + 0.1 * z^0$$

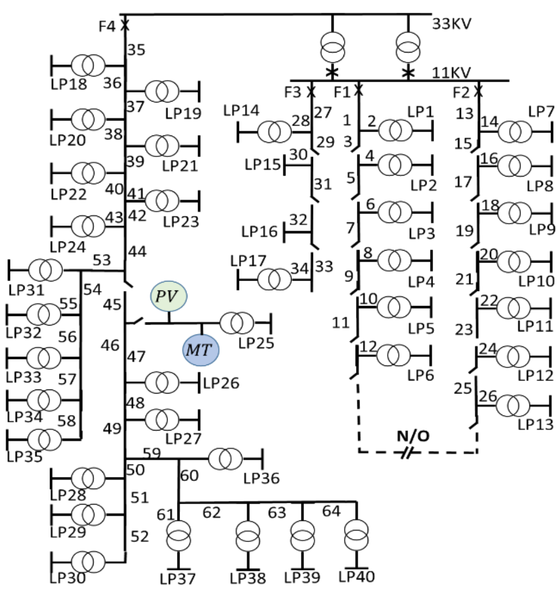


Figure 5. RBTS Bus 6 modified with distributed generation.

On the other hand, the load values are grouped into ten intervals of equal size in the range (156.75,277.6) kW for a reasonable trade-off between modeling precision and assessment efficiency [20]. The probability for each interval / state of charge is defined as the ratio of the number of load values within the interval to the total number of load values. For example, the state probability of the first interval / state is $\frac{371}{8760} = 0.042$. The state value for each interval / state is the average of the lower and upper limits of the interval. For example, the performance value for the first interval / state is $\frac{156.75+168.83}{2} = 162.8$. After grouping the load value and the state probability calculation, we can get the final function − u for the load:

$$U_L(z) = 0.084 * z^{271.6} + 0.249 * z^{259.5} + 0.138 * z^{247.4} + 0.088 * z^{235.3} + 0.059 * z^{223.2} + 0.09 * z^{211.1} + 0.076 * z^{199} + 0.129 * z^{187} + 0.043 * z^{174.9} + 0.042 * z^{162,8}$$

**CASE STUDY 1**

The solar irradiation data were taken from the meteorological station located at the University of Sucre, in the City of Sincelejo Colombia, obtaining the Normal distribution of solar irradiation, the resulting distribution is divided into 5 states of equal size according to [18], State probabilities are calculated using equations (13-14).The value of the expected solar irradiance, and the data of the solar panels are substituted in the generation function equation (1), to obtain the output power of a panel.

For case 1, the influence on the reliability of the system will be analyzed when photovoltaic distributed generators are introduced, for this, 1 photovoltaic generator will be entered whose peak power will be 300kW, for this, 750 solar panels of the JKM 400M-72H-V de 400 Wp of power, with a conversion efficiency $\eta_C = 19.72\%$, un $K_C = 300$andan area$S_P = 2.028m^2$. Table 1 shows the 5-state division information.

As described above, only two mechanical states are considered (for example, all solar modules work or all fail). The failure and repair rates established at $0.0005/h$ and y $0.013/h$, respectively[18]. After solving the Markov model, the operating and failure probabilities are$0.96$and$0.04$, respectively.

Table 1. Five-state solar model of a single solar module

| **Number of states** | **Solar irradiation ($kW/m^2$)** | **Probability** | **Output power (kW)** |
|---|---|---|---|
| 1 | 114.2 | 0.649 | 0.017 |
| 2 | 342.6 | 0.126 | 0.137 |
| 3 | 571 | 0.086 | 0.228 |
| 4 | 799.4 | 0.067 | 0.320 |
| 5 | 1027.8 | 0.071 | 0.411 |

With the above data the composite UGF model for the solar generator is

$$u_{PPV}(z) = u_I(z) \otimes_{\times} u_{PF}^1(z)$$

$$u_{PPV}(z) = (0.649z^{0.017} + 0.126z^{0.137} + 0.086z^{0.228} + 0.067z^{0.32} + 0.071z^{0.411}) \otimes_{\times} (0.96z^{750} + 0.04z^0)$$
$$= 0.04z^0 + 0.62z^{12.75} + 0.12z^{102.75} + 0.083z^{171} + 0.064z^{240} + 0.068z^{308,3}$$

By combining the UGFs of the solar generator with that of the distribution system, we obtain the complete generation function – u.

$$U_{G1}(z) = u_{PPV}(z) \otimes_{+} u_D(z)$$

$$U_{G1}(z) = 0.061z^{585.9} + 0.058z^{517.6} + 0.075z^{448.6} + 0.108z^{380.4} + 0.007z^{308.3} + 0.56z^{290.4} + 0.036z^{277.6} + 0.006z^{240} + 0.008z^{171} + 0.012z^{102.8} + 0.062z^{12.8} + 0.004z^0$$

With the generation and load functions – U of the system, the reliability indices are calculated for the system with distributed generation:

$$\text{LOLE} = 8760 \sum_{j=1}^{12} \sum_{i=1}^{10} p_j * p_i^L * \text{LLF}\left(g_j, g_i^L\right) = 777.8\,\text{hr/year}$$

$$\text{EENS} = 8760 \sum_{j=1}^{12} \sum_{i=1}^{10} p_j * p_i^L * \left(g_i^L - g_j\right) \text{LLF}\left(g_j, g_i^L\right) = 142{,}77\text{MWhr/year}$$

**CASE STUDY 2**

For case 2, the influence on the reliability of the system will be analyzed when Conventional generators (Diesel) are introduced, for this, 1 Diesel generator whose nominal power will be 280kW will be entered, the failure and repair rates are 0.000029 / h and 0.00091 / h [21], When solving the Markov model, the constant probabilities of the working and failure states are 0.97 and 0.03, respectively. Applying these values in the model given in section 2.5, The UGF model is then:

$$u_C(z) = 0.97 * z^{280} + 0.03 * z^0$$
$$u_D(z) = 0.9 * z^{277.6} + 0.1 * z^0$$

By combining the UGFs of the conventional generator with that of the distribution system, we obtain the complete generation function – u.

$$U_{G3}(z) = u_C(z) \otimes_{+} u_D(z)$$
$$U_{G3}(z) = 0.873z^{557.6} + 0.097z^{280} + 0.027z^{277.6} + 0.003z^0$$

With the generation and load functions – U of the system, the reliability indices are calculated for the system with distributed generation:

$$\mathrm{LOLE} = 8760\sum_{j=1}^{4}\sum_{i=1}^{10} p_j * p_i^L * \mathrm{LLF}\left(g_j, g_i^L\right) = 26.28\,\mathrm{hr/year}$$

$$\mathrm{EENS} = 8760\sum_{j=1}^{4}\sum_{i=1}^{10} p_j * p_i^L * \left(g_i^L - g_j\right)\mathrm{LLF}\left(g_j, g_i^L\right) = 5.99\mathrm{MWhr/year}$$

**CASE STUDY 3**

For case 3, the influence on the reliability of the system will be analyzed, when a combination of distributed photovoltaic and conventional generators is introduced, for this, 1 photovoltaic generator will be entered whose peak power will be 150kW, for this 375 solar panels and 1 Diesel generator will be used. whose nominal power will be 150kW, the same data given in sections 3.1 and 3.2 will be used. With the above data the compound UGF model for the solar generator is

$$u_{PPV}(z) = u_I(z) \otimes_\times u_{PF}^1(z)$$

$$u_{PPV}(z) = (0.649z^{0.017} + 0.126z^{0.137} + 0.086z^{0.228} + 0.067z^{0.32} + 0.071z^{0.411}) \otimes_\times (0.96z^{375} + 0.04z^0)$$

$$= 0.04z^0 + 0.62z^{6.4} + 0.12z^{51.4} + 0.083z^{85.5} + 0.064z^{120} + 0.068z^{154.1}$$

By combining the UGF of the solar generator with that of the Diesel generation system and that of the distribution system, we obtain the complete generation function − u.

$$U_{G3}(z) = u_{PPV}(z) \otimes_+ u_C(z) \otimes_+ u_D(z)$$

$$U_{G3}(z) = \frac{0.059z^{581.7} + 0.056z^{547.1} + \cdots + 0.019z^{6.4} + 0.00012z^0}{24\ \text{items}}$$

With the generation and load functions − U of the system, the reliability indices are calculated for the system with distributed generation:

$$\mathrm{LOLE} = 8760\sum_{j=1}^{24}\sum_{i=1}^{10} p_j * p_i^L * \mathrm{LLF}\left(g_j, g_i^L\right) = 693.95\,\mathrm{hr/year}$$

$$\mathrm{EENS} = 8760\sum_{j=1}^{24}\sum_{i=1}^{10} p_j * p_i^L * \left(g_i^L - g_j\right)\mathrm{LLF}\left(g_j, g_i^L\right) = 49.54\mathrm{MWhr/year}$$

Table 2

| Cases | LOLE (h) | EENS (MW) | % of improvement (EENS) |
|---|---|---|---|
| without DG | 876 | 199.77 | |

| | | | |
|---|---|---|---|
| Case 1 | 777.8 | 142.77 | 28.53% |
| Case 3 | 693.95 | 49.54 | 75.2% |
| Case 2 | 26.28 | 5.99 | 97% |

## IV. CONCLUSIONS

In this work, the universal generation technique was applied to evaluate the reliability of a distribution system, when conventional and renewable distributed generation systems are introduced, a simple system was used to clearly exemplify the use of the technique in this type of systems, also if we analyze the results of 3 case studies, it is observed that case study 2 presents a greater improvement in the reliability indicators, this system only uses conventional generation systems, therefore these systems do not represent any improvement since From an environmental point of view and they have a high operating cost, case study 1 shows the least improvement in reliability indicators, however, this option is the most viable from an environmental point of view and its operating costs are low , but its initial investment is higher, case study 3 is a combination of the 2 previous cases where the generation is divided by half, and the improvement of the indicators is also in the middle, these results agree perfectly with what the literature says, precisely this type of model allows finding the best combination between conventional generators and photovoltaic generators, depending on the item that is being evaluated (cost, environmental, reliability), in fact one of the advantages of the universal generation function is that it is easily coupled with optimization tools that offer the optimal solution.

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