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Reliability Assessment in Rural Distribution Systems With Microgrids: A Computational-Based Approach

JOSE L. LÓPEZ-PRADO[1], **JORGE W. GONZÁLEZ-SÁNCHEZ**[2], **(Senior Member, IEEE)**, **JORGE I. VÉLEZ**[3], **AND GUISSELLE A. GARCIA-LLINÁS**[3]

[1]Department of Electronic Engineering, Universidad de Sucre, Sincelejo 700001, Colombia
[2]Department of Electrical Engineering, Universidad Pontificia Bolivariana, Medellin 050004, Colombia
[3]Department of Industrial Engineering, Universidad del Norte, Barranquilla 081007, Colombia

Corresponding author: Jose L. López-Prado (lopezlj@uninorte.edu.co)

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ABSTRACT Rural distribution systems, especially in developing countries, tend to be less reliable than urban distribution systems because customers are (1) located remotely and (2) connected to weak aerial networks with radial topologies without redundancy. To improve reliability in rural areas, microgrids (MGs) are being integrated into conventional power systems. This study evaluates the effect on the reliability of rural distribution systems when MGs are introduced considering different penetration levels for renewable and nonrenewable distributed generation, and under rated power of energy storage. Here, we first formulate a reliability model for a rural distribution system with MGs. Based on this model, an interactive method using a sequential Monte Carlo simulation method is proposed and applied to calculate different conventional reliability indices. We show that this approach facilitates the selection of the parameters of the different systems constituting the MGs in order to comply with a predefined reliability objective. For instance, by introducing only photovoltaic distributed generation systems to the rural distribution systems under study, achieving the reliability objective is next to impossible. However, when correctly dimensioned-hybrid MGs are introduced, such an objective is successfully achieved. In the future, our model and the results provided herein could be combined with technical and economic studies to obtain an optimal solution that meets a certain reliability objective.

INDEX TERMS Microgrids, Monte-Carlo simulation, reliability evaluation, rural distribution systems.

NOMENCLATURE

AENS	Average Energy Not Supplied
ASAI	Average Service Availability Index
BESS	Batteries energy storage system
C	Component
CAIDI	Customer Average Interruption Distribution Index
CAIFI	Customer Average Interruption Frequency Index
$\Delta I(t)$	Random Amount of Attenuation at time t
DERs	Distributed Energy Resources
DG	Generation Distribution
DG-MT	Generation Distribution Micro-Gas Turbines
DG-PV	Generation Distribution Photovoltaics
EENS	Expected Energy Not Supplied Index
ENS	Energy Not Supplied
ESC	Energy Storage Capacity
ESS	Energies Storage System
FMEA	Failure Mode and Effective Analysis
$I_d(t)$	Solar Altitude Angle at Time t
I_{max}	Maximum Intensity of Sunlight per Day
$I(t)$	Solar Radiation Received at Time t
k_C	Threshold Value
$L_i(t)$	Load Value at Hour t
LP	Load Point
LPA	Load Points Analyzed
LPM	Load Points within the MG
LWF	Load Weighting Factor
MCS	Monte Carlo Simulation
MGs	Microgrids
MSC	Minimum Storage Capacity

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MT	Micro-Gas Turbines
NCE	Nominal Capacity (ESS)
η_C	Conversion Efficiency of the PV System
N_i	Number of customers at load point i
N_P	Number of Panels
P_{ai}	Average Load at Load Point i
$P_{DG,k}(t)$	Output of the kth DG at time t
P_{Charge}	Load Power
$P_{ChargeMax}$	Maximum Load Power
$P_{Discharge}$	Discharge Power
$P_{DischargeMax}$	Maximum Discharge Power
PI	Percentage of Improvement
p_{kj}	Control Parameter of Lateral Section k
PLDG-PV	Penetration Level DG-PV
$P_{li}(m)$	Peak Load Value for Load Point j
$P_L(t)$	Charge at Time t
PV	Photovoltaics
P_{PV}	Output Power
Q_{Remain}	Residual Energy in the ESS
Q_{Charge}	Energy Stored in the ESS in Island Mode
$Q_{Discharge}$	Energy Released from the ESS in Island Mode
Q_{Min}	Minimum Allowed Residual Capacity of the ESS
R	Set of Load Points in the RDS
RDS	Rural Distribution System
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
SMCS	Sequential Monte Carlo Simulation
UDS	Urban Distribution Systems
λ_j	Failure Index of Load Point
λ_{ij}	Failure Rates of the Main Section i
λ_{kj}	Failure Rates of the Lateral Section k
λ_{sj}	Failure Fates of the Series Element s
r_j	Interruption Duration
r_{ij}	Interruption Duration of the Main Section i
r_{kj}	Interruption Duration of the Lateral Section k
r_{sj}	Interruption Duration of the Series Element s
S_P	Area of a Solar Panel
t	Time in a day (hours)
T_{batt}	Operation Time
TTF	Time to Failure
TTR	Time to Repair
U_j	Mean Annual Interruption Time
$w_h(h)$	Weight Factor Per Hour for Load Point j
$w_m(m)$	Monthly Weight Factor for Load Point j

I. INTRODUCTION

One of the main features that causes power systems to fail is obsolescence in such technology, even in developed countries. Consequently, power systems have become unsustainable in time. For example, in Europe, great investments have been made to automate transmission grids, which represent approximately 3% of the complete system. Thus, more resources are needed to update the remaining system in which obsolete distribution grids represent >90% of it [1]. This scenario is more complex for developing countries where distribution grids are located in rural areas with low access or limited resources.

In Colombia, users connected to rural distribution systems (RDS) suffered power interruptions more than 900 times per year in 2018 [2]. Unfortunately, reports also indicate that this figure is ∼20 times higher than that in urban distribution systems (UDS) [2], which implies that RDS are less reliable than UDS. A possible explanation for this could be that these users are located in faraway regions connected by overhead networks with long distances. Consequently, any environmental phenomenon introduces failures into the system. In order to overcome interruption problems in RDS, different strategies have been recently reported in the literature, most of which are oriented toward updating the network architectures. One of these strategies is the introduction of Microgrids (MGs), which play an important role in improving efficacy, quality, performance, reliability, and cost [3]. MGs were conceived under the idea that producing and distributing energy within the same could place be a more robust and efficient process than transmission networks [4].

MGs can be understood as "*a group of interconnected loads and distributed energy resources (DERs) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes*" [5]. Thus, the MG concept matches perfectly with RDS, as their introduction can avoid the previously mentioned transmission-associated problems.

In the field of MGs, new tendencies focus on distribution systems where the generation process can be placed as close as possible to the user in order to reduce energy losses within the transmission process. Another advantage is the possibility of producing a system with the capability to operate separately (i.e., in island mode) from the main network when necessary [6]–[11]. Furthermore, MGs have been designed by including energy storage systems (ESS) and controllable loads, to improve the efficiency of the service while reducing costs. Thus, many operative conditions must be tuned in relation to subsystems and devices, with distributed energy resources (DERs) and the physical network being the most important. While DERs are generally constituted by an active load, a distributed generation (DG) system or an ESS, a physical network is required to connect all the devices used. This network includes advanced control systems, smart protection devices, and equipment for information and communications [12], [13].

Research literature indicates that the reliability of DS with MGs can be assessed using analytical (statistical) techniques and Monte Carlo Simulation (MCS) methods [14]. Within the analytical techniques, the tendency is to use approximate Markov methods [15]–[18] or hybrid systematic strategies that combine, among others, failure modes and effects analysis (FMEA), network models, the set of minimum cuts, and connection matrices [19]–[25]. Unfortunately, when the system is complex, analytical methods can be extremely difficult to apply. As some authors point out, in these circumstances computational methods such as MCS are more feasible. Recent studies have shown that it is possible to obtain very satisfactory results using sequential MCS (SMCS) [5], [26], [27].

Regarding the RDS, a considerable number of works have recently been presented in the literature demonstrating the current interest in these systems. As such, different characteristics have been analyzed, leveraging the consolidation of the concept. Indeed, the effect on the quality of an RDS has been analyzed when microgeneration PV are introduced [28], and the effect on reliability when MGs are introduced in the RDS was evaluated from the sustainability point of view while considering social and cultural characteristics [29], [30]. Furthermore, MGs were compared to underground networks from cost point of view (i.e., profitability), showing that the former could be a more economical option [31], [32]. Likewise, energy management strategies have been discussed in RDS with MGs [33].

Regarding reliability analysis in RDS with MGs, only three publications were identified. In the first publication, energy availability and reliability of solar power grids in rural areas were analyzed. In particular, seven picogrids in operation were studied. The authors collected data in the field, performed interviews and measurements, and determined the number of user failures per week and the availability of the system [34]. This study concluded that assessing the reliability of installed power systems will be increasingly important in the coming years, especially now that the PV market in emerging economies, and particularly in India, is booming with new market players and system providers [34]. However, the authors did not compute any reliability index to assess the impact of these on the system. In the second publication, the authors quantified the benefits of MGs in the RDS using some metrics such as the probability of loss of load [35], but they do not focus on a reliability analysis as such. In the third publication, the authors evaluated some Smart Grid (SG) functions that improve the reliability of rural electricity networks. The main focus of this study was reliability analysis. In the third publication, the authors evaluated some Smart Grid functions that improve the reliability of rural electricity networks. The main focus of this study was reliability analysis. Thus, the authors calculated several reliability indices using an analytical method [36].

In the literature reviewed, we identified that the reliability assessment in RDS with MGs using computational methods has not yet been explored. Therefore, here we propose a method to evaluate, via SMCS, the effect of introducing MGs on the reliability of an RDS when different penetration levels of DG, renewables or nonrenewable energies, and the nominal capacity (ESS) are considered. Using our approach, we select the parameters of the MG that guarantee the system's reliability for a short, medium, and longtime range [2] according to Colombia's regulations. The method was subsequently applied to data from real RDS. The remainder of this paper is organized as follows. Section 2 presents the modeling of the reliability parameters in an RDS when MGs are introduced. In Section 3, the reliability assessment method is described. Next, in Section 4, the application of our SMCS method to real data of an RDS is presented, emphasizing the impact of introducing MGs into this RDS on its reliability. Finally, the results, conclusions, and lines of future research are presented.

II. RURAL DISTRIBUTION SYSTEM WITH MICROGRIDS APPLICATIONS OVERVIEW

Here, we analyze an RDS with their respective loads when MGs, consisting of photovoltaic (PV) and micro-gas turbines (MT) DGs, and battery ESS (BESS), are included. In addition, two reliability-related aspects were considered: (1) the availability of resources, which represents the availability of solar radiation in the required amount, and (2) the availability of equipment that represents the active or failed state of the DS with MGs. Fig. 1 illustrates the block diagram of the RDS reliability assessment model when the MGs are introduced.

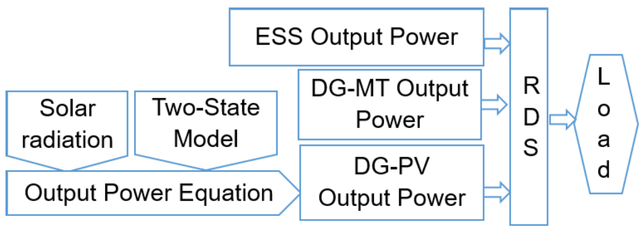

FIGURE 1. Reliability evaluation model of a real RDS with MGs. BESS: Batteries energy storage system, DG: Distribution Generation, MT: Micro-gas Turbine, PV: Photovoltaic.

A. RURAL DISTRIBUTION SYSTEMS

The distribution system (DS) is the final section of the power system and provides a link between the consumers' load points and the generation and transmission systems. The basic function of a DS is to supply electrical power from a substation to the customers' load points. Many DS used in practice, especially RDS, have a single circuit main feeder and are defined as radial RDS [37]–[39].

1) RELIABILITY EVALUATION IN A RDS

An RDS is usually represented by a general feeder consisting of n main sections, m side sections, and one component in series. Considering the basic function of a DS, the continuity of service is an important criterion. This can be described by three basic load indices: (1) the average failure rate, (2) the average interruption time, and (3) the average annual interruption time. For an RDS, based on the data of the elements ($\lambda_i, \lambda_k, \lambda_s, r_i, r_k, r_s, p_k$) and the series configuration of the general feeder, these three basic load indices are calculated based on the failure index of load point λ_j, duration r_j and mean annual interruption time U_j for load point j of a general feeder using the following set of general formulas [19]:

$$\lambda_j = \lambda_{sj} + \sum_{i=1}^{n} \lambda_{ij} + \sum_{k=1}^{m} p_{kj} \times \lambda_{kj} \quad (1)$$

$$U_j = \lambda_{sj} \times r_{sj} + \sum_{i=1}^{n} \lambda_{ij} \times r_{ij} + \sum_{k=1}^{m} p_{kj} \times \lambda_{kj} \times r_{kj} \quad (2)$$

$$r_j = \frac{U_j}{\lambda_j} \quad (3)$$

where P_{kj} is the control parameter of the lateral section k, which depends on the operating model of the fuse. By definition, P_{kj} can take values of 1 or 0 corresponding to no fuse or 100% reliable fuse, respectively, or a value between 0 and 1 for a fuse with probability of failure P_{kj}. Here we set $P_{kj} = 1$. On the other hand, the parameters λ_{ij}, λ_{kj} and λ_{sj} are the failure rates of the main section i, the lateral section k and the series element s, respectively; and r_{ij}, r_{kj} and r_{sj} are the interruption duration (switching time or repair time) for the three elements. As expected, and have different values for different load points when different alternate supply modes of operation are used, and disconnect switches are installed at distinct locations in the feeder [19].

B. RELIABILITY MODEL OF THE FINAL LOAD

In an electrical system, weather conditions and seasonal events affect load values. Therefore, the charging behavior of the power system exhibits a repeating pattern under normal conditions. Consequently, a variable load model can be developed over time using historical data [40]. Hence, monthly and hourly weighting factors were used to build a load model over time using the proposed modeling method. The estimated load for the jth load point at a given time for different sectors (i.e., residential, commercial and industrial) can be calculated as [40]–[43]:

$$L_j(t) = W_h(h) \times W_m(m) \times P_{lj} \quad (4)$$

where $L_j(t)$ is the load value at hour t, and $W_h(h)$, $W_m(m)$ and P_{lj} are the weight factor per hour, the monthly weight factor, and the peak load value for the load point j, respectively. Fig. 2 shows the monthly and hourly weight factors estimated for the RDS object of study in this study.

C. RELIABILITY MODEL IN CONVENTIONAL DG UNITS

In this work, conventional MT units are used as they are less polluting than diesel units and are available in the region of the case study. Regarding the reliability model, a two-state model is used (Fig. 3), as it can be applied to any conventional system.

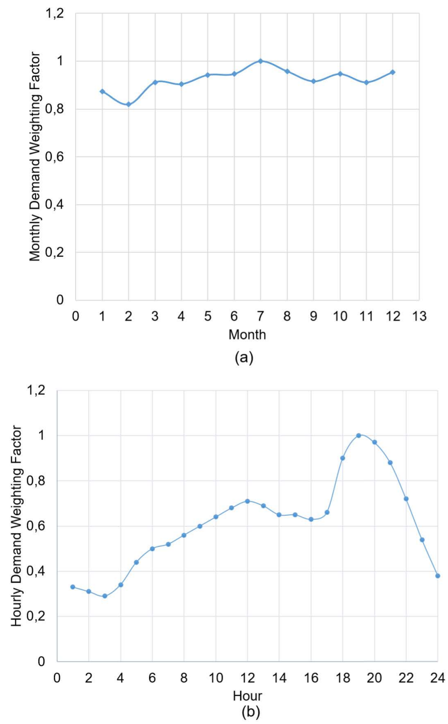

FIGURE 2. (a) Monthly and (b) hourly demand weighting factors for a Colombian RDS.

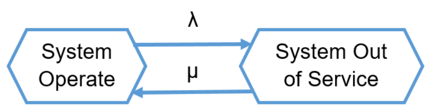

FIGURE 3. Two-state model for a repairable single component system.

D. STOCHASTIC POWER MODEL OF THE OUTPUT SYSTEM

PV devices are robust, simple in design, and require little maintenance. PV generation directly converts sunlight into electricity without interference from any heat engine. The main advantage of PV systems is their construction, as independent systems, to provide power ranging from micro to megawatts [44]–[46]. The solar panel is the central element of a PV system; its output depends on several factors such as solar radiation or the intensity of sunlight received by the panel, temperature, and relative humidity, among others, being the most important solar radiation, which varies from month to month, as illustrated in Fig. 4(a).

Let $I(t)$ be the solar radiation received at time t. Then, the output power P_{PV} of the solar panel is given by [27], [40], [43], [47].

$$P_{PV} = \begin{cases} \frac{\eta_c}{K_c} \times S \times I(t)^2 & 0 < I(t) \leq K_c \\ \eta_c \times S \times I(t) & I(t) > K_c \end{cases} \quad (5)$$

where η_c is the conversion efficiency of the PV system, including the inverters, and K_c is a threshold value. When $I(t) \leq K_c$, η_c varies linearly, and P_{PV} has a second-order relationship with $I(t)$. When $(t) \geq K_c$, η_c is usually constant,

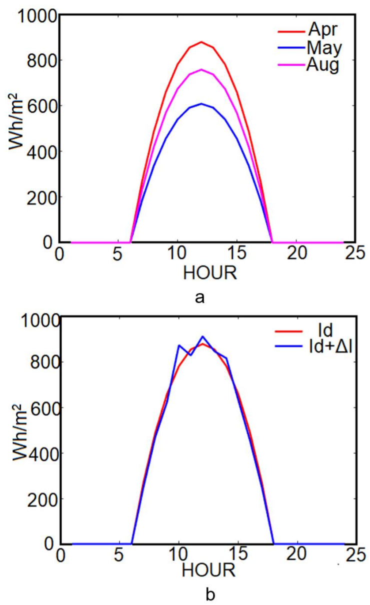

FIGURE 4. (a) Solar radiation $I_d(t)$ for April, May and August; (b) typical variation of solar radiation received by a solar panel in one day, for Colombia.

and P_{PV} has a linear relationship with $I(t)$. On the other hand,

$$S = S_p \times N_p \quad (6)$$

where S_p is the area of the solar panel, and N_p is the number of panels.

Solar radiation depends mainly on the solar altitude angle and the attenuation effect of cloud occlusion. The variation of the solar altitude angle with time in a day can be determined by a definitive function, while the occlusion of the clouds is random as the weather changes. Thus, $I(t)$ can be calculated as [27].

$$I(t) = I_d(t) + \Delta I(t) \quad (7)$$

where $\Delta I(t)$ is the random amount of attenuation and $I_d(t)$ is the solar altitude angle. The latter is defined as the average value of sunlight at time t in a statistical time range (usually one year). If the change in sunrise and sunset times during the year is not considered, $I_d(t)$ can be approximated by the following quadratic function [27]:

$$I_d(t) = \begin{cases} I_{max}\left(-\frac{1}{36}t^2 + \frac{2}{3}t - 3\right) & 6 \le t < 18 \\ 0 \quad 0 \le t < 6,\ 18 \le t < 24 \end{cases} \quad (8)$$

In the equation above, t is the time in a day (hours), and I_{max} is the maximum intensity of sunlight in a day. In our approach, it is assumed that the maximum intensity occurs at noon, that is, $I_{max} = I(12)$.

Studies have shown that the variation in $I(t)$ follows a Normal distribution [40], [43]. Fig. 4(b) shows the typical variation in the intensity of sunlight received by a solar panel in one day [27]. For simplicity, it is assumed that $\Delta I(t)$ follows a standard Normal distribution.

1) RELIABILITY MODEL OF THE PV SYSTEM

To obtain the reliability model of a PV system, a combination of the two-state model used in the MT system reliability model and the PV system output power model given in Equation 5 was used (Fig. 1 and Fig. 3).

E. STORAGE SYSTEM RELIABILITY MODEL COMBINED WITH DG

Owing to its operational characteristics, the representation of batteries in reliability studies requires a particular model. It is generally accepted that the behavior of batteries is not Markovian because their charge state depends on the operation of the system; thus, it is difficult to establish a model for its operation. Furthermore, their service life, which depends on the charge/discharge cycles, must be considered, and a possible failure not related to service life, such as a failure caused by a battery defect, must also be included in the model [24]. However, these characteristics are not essential when it is necessary to quantify the impact of putting batteries in parallel with the DG to supply the energy not supplied by the generators for any reason. In this case, battery availability was used to quantify their influence on the reliability indices.

To improve the power quality and reliability of the power supply in the MG, we combine batteries with intermittent generation, such as PV, to smooth fluctuations in the output of these DGs. In island mode, when the DG output is greater than the load, the residual energy is stored in the ESS according to its load capacity. When the DG output is less than the load, the stored energy is released to supply customers, considering the discharge capacity of the storage system, assuming that the combined DGs and the ESS are autonomous and controllable. Neglecting the influence of time on power regulation, it can be assumed that the combined DG output and the load and ESS can reach equilibrium at any moment in time [27].

However, the DG-PV power output may be insufficient for any of the following three situations: (1) DG failures, (2) absence of light at night, or (3) insufficient light during the day. When any of these situations occur while the MG is in island mode, the ESS has to release energy. Because the ESS operation time is limited by its storage capacity, it is necessary to determine the operation time of the hybridized DG with the ESS in island mode. This time, denoted as T_{batt}, can be solved using the following set of equations:

$$Q_{Min} = Q_{Remain} + Q_{Charge} + Q_{Discharge}; \quad (9)$$

where

$$Q_{Charge} = \int_0^{T_{batt}} \left[\sum_k P_{DG,k}(t) - P_L(t)\right] dt, \quad (10)$$

when $P_L(t) < P_{DG}(t)$ is the energy stored in the ESS in island mode;

$$Q_{Discharge} = \int_0^{T_{batt}} \left[P_L(t) - \sum_k P_{DG,k}(t)\right] dt, \quad (11)$$

when $P_L(t) > P_{DG}(t)$ is the energy released from the ESS in island mode; and Q_{Min} is the minimum allowed residual capacity of the ESS.

In the expressions above, $P_L(t)$ represents the charge at time t; $P_{DG,k}(t)$ represents the output of the kth DG at time t; Q_{Remain} is the residual energy in the ESS at the beginning when the MG switches to island mode. In this scenario, the ESS can be considered as fully charged because, when the MG is connected to the RDS, it can charge the storage system if necessary. As mentioned above, the load power P_{Charge} is limited by the maximum load power $P_{ChargeMax}$ of the storage system, that is,

$$P_{Charge} = \sum_k P_{DG,k}(t) - P_L(t) \leq P_{ChargeMax} \quad (12)$$

Similarly, the discharge power $P_{Discharge}$ is limited by the maximum discharge power $P_{DischargeMax}$ of the storage system, that is,

$$P_{Discharge} = P_L(t) - \sum_k P_{DG,k}(t) - P_L(t) \leq P_{DischargeMax} \quad (13)$$

The set of equations (9)-(11) are implicit integration equations, which are difficult to solve using analytical methods. However, they can be solved by simulating the DG outputs and hourly loads in island mode.

III. METHODS AND PROCEDURES TOWARD THE RELIABILITY ASSESSMENT IN RURAL DISTRIBUTION SYSTEM

A. SEQUENTIAL MONTE-CARLO SIMULATION

MCMC methods are the general designations for stochastic simulations using random numbers. In the reliability evaluation using Sequential Monte Carlo simulation (SMCS) methods, reliability indices are estimated by simulating the operation of the real process and the random behavior of the system. Therefore, this method treats the problem as a series of experiments [48]. In theory, SMCS can consider practically all aspects and contingencies inherent in the planning, design, and operation of a DS, including random events such as load variations and the generation, interruptions, and repairs of elements represented by probability distributions.

When using SMCS methods, the duration of the state for the components of each system is determined by sampling from its corresponding probability distribution. In this technique, the time-state transition processes of such components are first simulated by sampling. The next step is to combine these results to create a chronological state transition process for the entire system for a pre-specified simulation time. This is achieved by using probability distributions that resemble the duration of the state for each component. In a two-state component representation, these are the operation and repair state duration distribution functions, which are generally assumed to follow an Exponential distribution. However, other probability distributions can be used [42], [49]. In Section III.C, we propose an algorithm for the reliability evaluation of the RDS with applications of MGs using SMCS.

B. ADEQUACY INDICES OF THE RDS

The performance indices for the DS can be calculated using the basic indices presented in equations (1)-(3). Some examples of these performance indices include the Customer Average Interruption Frequency Index (CAIFI), Customer Average Interruption Distribution Index (CAIDI), Energy (Power) Not Supplied (ENS), Average Energy (Power) Not Supplied (AENS), Average Service Availability Index (ASAI), System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Expected Power Not Delivered Index (EENS). The SAIFI, SAIDI, and ENS indexes can be calculated as follows:

$$SAIFI = \frac{\sum_{i \in R} \lambda_i N_i}{\sum_{i \in R} N_i} \quad (14)$$

$$SAIDI = \frac{\sum_{i \in R} U_i N_i}{\sum_{i \in R} N_i} \quad (15)$$

$$ENS = \sum_{i \in R} P_{ai} U_i \quad (16)$$

where λ_i, U_i and N_i are the average failure rate, the average annual interruption time in hours per year, and the number of customers at load point i, respectively. In addition, R is the set of load points in the system, and P_{ai} is the average load (in kW) connected to load point i.

C. RELIABILITY ASSESSMENT ALGORITHM OF RDS WITH MGs-DG-PV VIA SMCS

The general algorithm proposed for the reliability evaluation of the RDS with applications of MGs based on the SMCS is presented in Fig. 5 and described further below. The necessary data to run the simulation is presented in section IV.C.

Step 1: Start by setting the stopping criterion. In this case, we consider the maximum number of simulation years, which was set as $Years = 5000$.

Step 2: Define the input parameters, which include the failure (λ) and repair (μ) rates for each RDS and MG component (i.e., DG-PV, DG-MT, and ESS), the number of clients (N_i) at each load point (LP), the historical data of the peak load in each LP, the historical data of solar radiation, and the characteristics of the DG-PV, DG-MT, and ESS.

Step 3: Initialize the simulation process. Set the initial state of all components to run, the initial simulation time ($t = 0$), the simulation hours T to $T = 8760$, and the initial number of years n to $n = 1$.

Step 4: While, $n \leq Years$, go to the next step; otherwise, go to step 18.

Step 5: Generate a random number from a $U(0, 1)$ for each component of the RDS and for each system of the MG (DG-PV, DG-MT, and ESS) according to the two-state model given in Section II.C. Then, the time to failure (TTF) was calculated as $TTF = -\frac{1}{\lambda}\ln(U)$ and time to repair (TTR) as

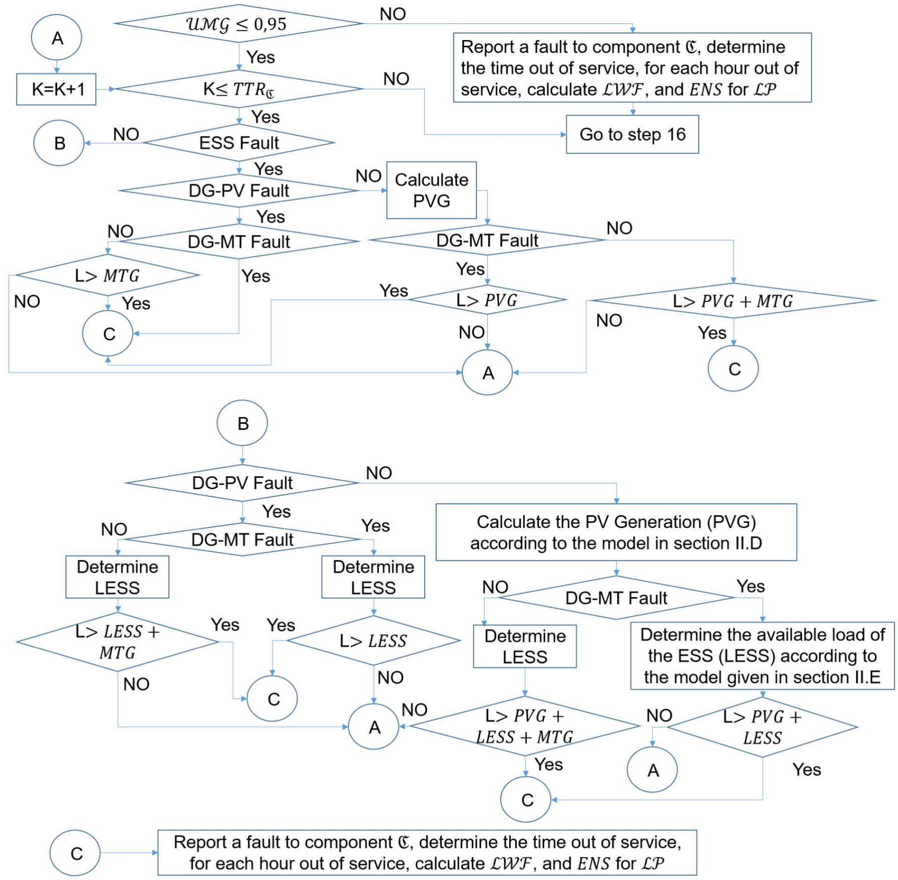

FIGURE 5. Flow diagram for the reliability assessment of the RDS with MG-DG-PV via SMCS methods.

$TTR = -\frac{1}{\mu}\ln(U)$. Using SMCS for one year, the operating history for each component is in the form of ascending-descending chronological operating cycles. Finally, we find the C component of the RDS with the minimum TTF and assign the TTF to TTF_C.

Step 6: While $TTF_C \leq T$, go to the next step; otherwise, go to step 17.

Step 7: Define C as the failed component. If the failed component is a transformer, proceed to the next step; otherwise, go to step 9.

Step 8: If only the LP where the transformer is connected fails, determine the location of C and report a failure to component C. Further, determine the time out of service. For each hour out of service, calculate the load weighting factor (LFW) according to the model given in Section II.B, and the ENS for LPs according to equation 16. Go to step 16.

Step 9: Determine the location of C. If the failed component is outside the MGs, proceed to the next step; otherwise, go to step 12.

Step 10: For LPs outside the MGs, report a failure to component C. Determine the downtime. For each hour out of service, calculate LWF, and ENS for LPs. Go to the next step.

Step 11: For LPs within the MG, the analysis is performed depending on the characteristics of the MG. For example, for an MG with DG-PV-MT-ESS, go to the MG algorithm given in Fig. 5.

Step 12: If the soft-shift reconnect works, proceed to the next step; otherwise, go to step 14.

Step 13: For LPs failing within the MGs, report a failure to component C. Determine the time out of service. For each hour out of service, calculate LWF and the ENS for LPs. Go to step 16.

Step 14: If all LPs fail except those found within other MGs, report a failure to component C for LPs that are out of other MGs. Determine the time out of service and calculate LWF, and ENS for LPs. Go to next step.

Step 15: For LPs within other MGs, the analysis is performed depending on the characteristics of the MG. For example, for an MG with DG-PV-MT-ESS, go to the algorithm shown in Fig. 5.

Step 16: Generate a new random number for component C and transform it into a new TTF_n, $t = TTF_C + TTR + TTF_n$. Assign t to TTF_C and find the next C component of the RDS with the minimum TTF. Set TTF to TTF_C, and proceed to step 6.

Step 17: Calculate λ and U for the LPs, calculate $n = n + 1$ and go to step 4.

Step 18: Calculate the system reliability indices for the sample years and End.

IV. COMPUTATIONAL VALIDATION THROUGH A STUDY CASE

A. SELECTION OF THE RDS

In order to (1) evaluate the effect on reliability when interconnecting MGs in the RDS, and (2) to evaluate the reliability of a real DS, we use a Colombian RDS. Thus, in this section, we emphasize the reliability diagnosis of a Colombian DS.

1) RELIABILITY DIAGNOSIS OF THE COLOMBIAN DISTRIBUTION SYSTEM

Based on the quality diagnosis of the electricity service in Colombia performed by the *Superintendencia de Servicios Públicos* Domiciliarios in 2018 [2], two conclusions can be drawn. First, users of the Colombian Caribbean region receive the electric power service with the worst reliability indicators in the country. Secondly, when the quality of the service was analyzed for each municipality in the country, the results indicated that in some municipalities, which generally correspond to rural territories, the average duration of interruptions per user is 800 hours with an average number of interruptions per user of 900 times during 2018 alone. These figures are more than 20 times higher than those reported countrywide.

2) SAIDI AND SAIFI INDICATORS

In 2018, the SAIDI and SAIFI reliability indices for the RDS under study were 226.4 times and 106.9 times, respectively, which dramatically exceed the country's indicators. Thus, performing a reliability assessment of the Colombian RDS is relevant, especially for the Colombian Caribbean region. Fig. 6 shows the SAIFI reliability index for the RDS as reported by different companies during 2017 and 2018.

B. DESCRIPTION OF THE RDS UNDER STUDY

As previously mentioned, here we use a RDS of the Colombian Caribbean region. Specifically, we used data from the municipality of Morroa, located in the Department of Sucre (latitude: 9.20°, longitude: -75.18°). Morroa is a municipality where approximately 58.6% of its 12784 inhabitants live in rural areas. Fig. 7 shows the one-line diagram of the RDS that will be used in this case, which corresponds to a radial system with a supply point, without external power, and two feeders or branches F1 and F2, all of which are loads of residential type. In this system, all the main and lateral feeders are overhead lines.

Table 1 shows the lengths in kilometers (km) of each feeder. Furthermore, each branch has a single protection device that disconnects the branch when a fault occurs in it, that is, in the event of a failure in any of the branch lines (main or lateral), the entire branch fails. In addition, each transformer has protection devices that isolate it in the event of a fault.

TABLE 1. Length of the feeders.

Feeder number	Length(km)	Feeder number	Length (km)
1	12	5, 6, 7, 10, 28, 30	1
21	9	14	0.9
2	7	16	0.8
4	5	13, 20, 31, 32	0.7
24, 27	3.7	9	0.6
26	2	11, 17, 25	0.5
3, 22	1.5	23	0.4
15	1.3	8, 18	0.3
29	1.1	12, 19	0.2

TABLE 2. Customer data for the Colombian RDS under study.

Load point (LP)	Peak demand per LP (Watts)	Number of users
F1		
1	2576	1
2	3520	3
3	4488	5
4	5464	7
5	3048	2
6	22512	41
7	6448	9
8	9440	15
9	4488	5
10	2576	1
11	19520	35
12	32080	60
13	13024	22
14	18992	34
Total	148176	240
F2		
15	11448	19
16	2576	1
17	2576	1
18	2576	1
19	2576	1
20	2576	1
21	2576	1
22	2576	1
Total	29480	26

C. CUSTOMER AND LOADING DATA

Table 2 lists the number of customers and peak demand per charging point.

Due to confidentiality restrictions, the load data was not provided by the service provider company. Thus, the monthly weighting factor (Fig. 2a) was estimated using the information contained in the Monitoring of the Regional Electric Power Demand Projections (Coast-Caribbean region) section of the document "*Proyección Regional de la Demanda de Energía Eléctrica y Potencia Máxima en Colombia de Abril del 2019*" [50] by the *Unidad de Planeación Minero Energética (UPME) de Colombia*. Furthermore, the hourly weighting factor (Fig. 2b) was estimated from the document "*Criterios de Diseño de la Red de Electrificación Rural*" [51], which was prepared by *Electrificadora de Santander* (ESSA). Specifically, the daily demand curves for strata 1 and 2 for the residential sector were used.

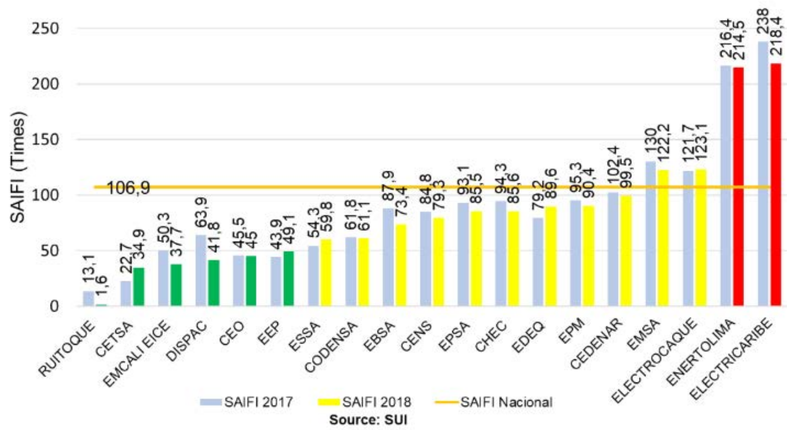

FIGURE 6. SAIFI by Operator vs. National SAIFI for quality group 4 during 2018. Here, the yellow horizontal line represents Colombia's average SAIFI. SUI = Unique information system on home public services.

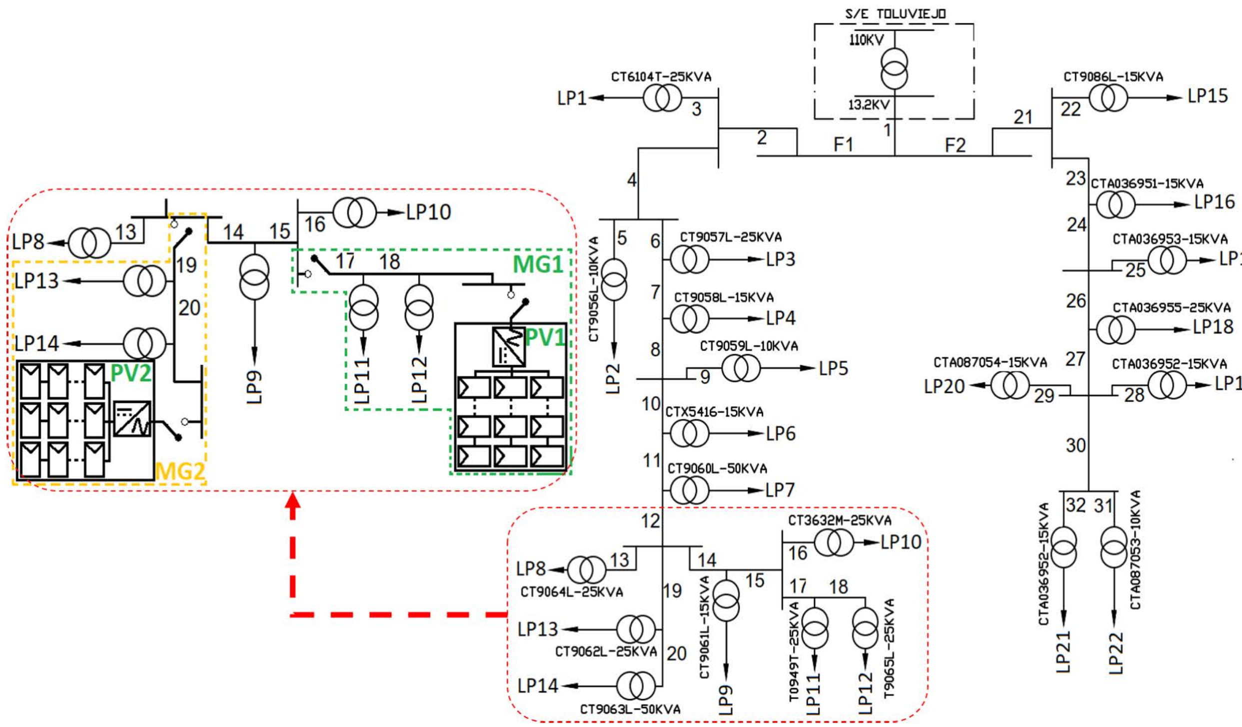

FIGURE 7. Colombian RDS with a MGs-PV configuration.

D. SYSTEM RELIABILITY DATA

The reliability data assumed for the system components reported in Table 3 were estimated from [52], which presents the reliability data for the Colombian distribution system. In addition, [53] and [54] were considered.

TABLE 3. Estimated system reliability data for the Colombian distribution system. * Failure rates on lines are per km of circuit; MTTR: mean time to repair.

Component	λ_p (by year)	MTTR (hours)	
		Mean	Standard deviation
Transformer	0.04783	0.5	0.6
Lines	**6***	11.7	2.5

E. ASSESSMENT OF THE IMPACT OF THE DG-PV PENETRATION LEVELS ON RDS RELIABILITY

Considering that the diagnostic of the RDS showed worrying figures in the SAIFI reliability index, we introduced two MGs to the Colombian RDS, as shown in Fig. 7. In the modified RDS, both MG1 and MG2 contained a DG-PV without storage. Table 4 shows the reliability parameters for the DG-PV. Real meteorological data were provided by the *Instituto de*

Hidrología, Meteorología y Estudios Ambientales (IDEAM), which is responsible for managing scientific, hydrological, and meteorological information and everything related to the environment in Colombia. The selected data correspond to the EL TESORO station located in the municipality of Morroa, Sucre. Table 5 shows the average of the highest solar radiation (at noon) per month. The SMCS model was ran for one year using 5000 simulations to guarantee the convergence.

TABLE 4. Reliability parameters by MG component for the modified RDS in Fig. 7.

MG Component	λ (faults/year)	MTTR (hours)
PV1	0.12	72
PV2	0.12	72
MT1	0.18	12
MT2	0.18	12
ESS1	0.05	50
ESS2	0.05	50

TABLE 5. Estimated monthly average solar radiation $\left(\frac{Wh}{m^2}\right)$ in Morroa, Sucre.

Month	January	February	March	April
Solar radiation	768.3	810.4	807.7	878
Month	May	June	July	August
Solar radiation	607.5	760.3	757.1	813.3
Month	September	October	November	December
Solar radiation	711.3	729.6	676.7	685.8

1) IMPACT OF DG-PV PENETRATION LEVELS ON THE RDS RELIABILITY

To estimate the impact of different penetration levels of a DG-PV on the reliability of an RDS, we evaluated seven scenarios. In particular, the DG-PV was varied by considering penetration levels of 50%, 75%, 100%, 150%, 200%, 400%, and 1000%. Subsequently, reliability indices with respect to a load point (LP) with and without the introduction of MGs were calculated using the proposed model (Fig. 5). As illustrated in Figs. 8 (a) and (b), the reliability results were expressed in terms of the failure rate and the mean annual interruption time for the load points within the MG (LPM). In addition, the SAIFI, SAIDI, and ENS reliability indexes for the LPM and F1 feeder were calculated for both the current and modified RDS (Table 6). Fig. 9 (a) and (b) show a graphical representation of these results.

Our findings suggest that (1) using DG-PV with penetration levels less than or equal to 75% do not significantly contribute to increase the reliability of the RDS; (2) penetration levels between 100% and 150% provided the best reliability; and (3) increasing the penetration level up to 150% does not significantly increase the reliability. Indeed, going from 150% to 1000% penetration only improves the SAIFI of the F1 feeder by 6.3%.

On the other hand, when analyzing the expected reliability values in Colombia for 2028 (Table 7) [55], we see that by using the current RDS configuration or introducing

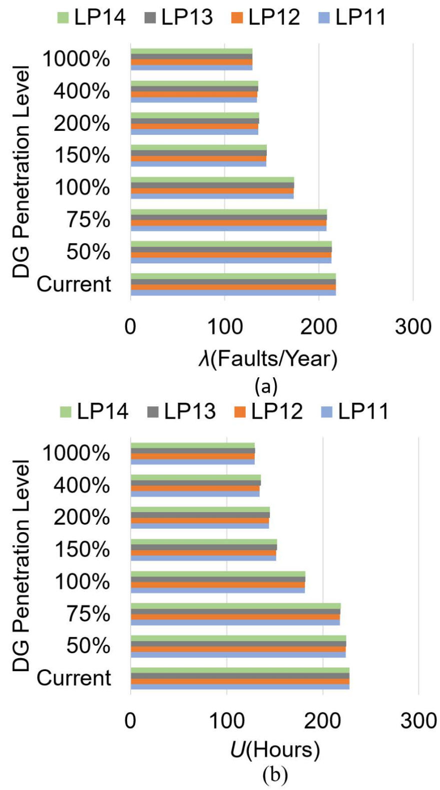

FIGURE 8. (a) Failure Rate and (b) Average Annual Interruption Time for each LPM by MG penetration level.

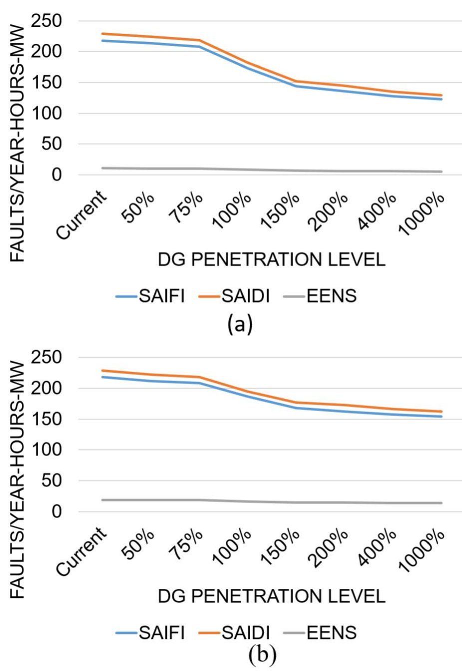

FIGURE 9. SAIFI, SAIDI and ENS reliability indices for the (a) LPM and (b) F1 feeder as a function of the MG penetration level.

different DG-PV penetration levels would be almost impossible to comply with such reliability expectations. Therefore, introducing hybrid MG systems combining different types of

TABLE 6. Reliability indices for the modified RDS for different DG-PV penetration levels.

PLDG-PV*	Reliability index	LPA	PI(%)**	F1	PI(%)**
Actual	SAIFI	218	-	218	-
0%	SAIDI	228.7	-	228.7	-
	ENS+	10.75	-	19.05	-
50%	SAIFI	213.4	2.09	211.6	2.89
	SAIDI	224.3	1.91	222.5	2.73
	ENS+	10.54	1.89	18.85	1.01
75%	SAIFI	208.1	4.53	208.2	4.49
	SAIDI	218.2	4.58	218.2	4.57
	ENS+	10.23	4.82	18.5	2.88
100%	SAIFI	173.3	20.5	186.2	14.6
	SAIDI	181.7	20.5	195	14.7
	ENS+	8.328	22.5	16.58	12.9
150%	SAIFI	144.2	33.8	167.9	22.9
	SAIDI	152.1	33.5	176.8	22.7
	ENS+	6.869	36.1	15.16	20.4
200%	SAIFI	135.8	37.7	162.6	25.3
	SAIDI	144.4	36.8	172.6	24.5
	ENS+	6.492	39.5	14.84	22.1
400%	SAIFI	127.8	41.4	157.8	27.6
	SAIDI	134.8	41	166.1	27.3
	ENS+	6.042	43.8	14.35	24.6
1000%	SAIFI	122.5	43.7	154.4	29.2
	SAIDI	129.4	43.4	162.6	28.9
	ENS+	5.731	46.6	14.03	26.4

** Percentage of improvement (%); + ENS (MW).

TABLE 7. Colombian reliability goal.

Index	Year		
	2016	2023	2028
SAIDI	38	25	17
SAIFI	49	32	21

DG into the paradigms of the current RDS could potentially help to improve its reliability. This scenario is analyzed in the next section.

F. ASSESSMENT OF THE IMPACT OF INTRODUCING MGS WITH DG-PV-MT AND ESS ON THE RDS RELIABILITY

To comply with the reliability objectives established for Colombia, we introduced two MGs to the Colombian RDS presented in Fig. 7. In this modified RDS system (Fig. 10), both MG1 and MG2 contain two DGs, one PV and one MT, and an ESS system. The reliability parameters of the DG-PV, DG-MT, and ESS are reported in Table 5. The SMCS was evaluated for one year using 5000 simulations.

1) DG-PV-ESS PENETRATION ASSESSMENT

We evaluated three scenarios to analyze the impact of different DG-PV-ESS-MT penetration levels on the modified Colombian RDS. In particular, the DG-MT penetration level varied in {10%, 20%, 50%} for each MG, and the nominal capacity ESS (NCE) changed in {25%, 50%, 75%, 100%}, resulting in 12 different scenarios. In all of them, the DG-PV penetration level was set to 100%, and the energy storage capacity (ESC) was set to 100% of the peak load with a minimum storage capacity (MSC) of 10%.

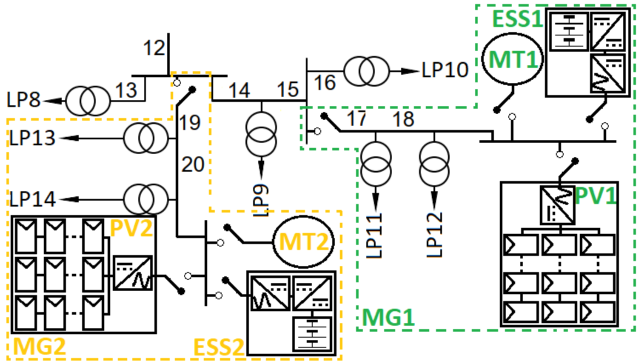

FIGURE 10. Modified Colombian RDS when a MGs-PV-ESS-MT are introduced. MG: Microgrid, PV: Photovoltaic, ESS: Energy storage system, MT: micro-gas turbine.

TABLE 8. Reliability indices for the modified colombian rds. Here, DG-PV = 100%, ESC = 100% and MSC = 10%.

DG-MT = 10%					
NCE		**LPA**	**PI(%)**	**F1**	**PI(%)**
Current	SAIFI	217.95		217.95	
	SAIDI	228.68		228.70	
	ENS+	10.747		19.046	
25%	SAIFI	93.842	56.9	136.42	37.4
	SAIDI	99.557	56.5	143.91	37.1
	ENS+	5.228	51.4	13.529	29
50%	SAIFI	55.725	74.4	112.32	48.5
	SAIDI	59.246	74.1	118.40	48.2
	ENS+	3.685	65.7	11.972	37.1
75%	SAIFI	32.972	84.9	98.046	55
	SAIDI	36.478	84.1	103.94	54.6
	ENS+	2.132	80.2	10.406	45.4
100%	SAIFI	18.137	91.7	88.651	59.3
	SAIDI	21.758	90.5	94.991	58.5
	ENS+	0.952	91.1	9.255	51.4
DG-MT = 20%					
NCE		**LPA**	**PI(%)**	**F1**	**PI(%)**
25%	SAIFI	74.17	66	123.82	43.2
	SAIDI	79.17	65.4	131.07	42.7
	ENS+	4.491	58.2	12.796	32.8
50%	SAIFI	46.919	78.5	106.90	51
	SAIDI	50.438	78	113.18	50.5
	ENS+	3.165	70.5	11.482	39.7
75%	SAIFI	20.411	90.6	90.049	58.7
	SAIDI	23.623	89.7	95.845	58.1
	ENS+	1.142	89.4	9.417	50.6
100%	SAIFI	17.621	91.9	88.260	59.5
	SAIDI	21.185	90.7	94.761	58.6
	ENS+	0.924	91.4	9.241	51.5
DG-MT = 50%					
NCE		**LPA**	**PI(%)**	**F1**	**PI(%)**
25%	SAIFI	44.476	79.6	105.33	51.7
	SAIDI	47.478	79.2	111.19	51.4
	ENS+	2.977	72.3	11.283	40.8
50%	SAIFI	16.337	92.5	87.513	59.8
	SAIDI	17.777	92.2	92.239	59.7
	ENS+	0.834	92.2	9.112	52.2
75%	SAIFI	16.057	92.6	87.5	59.9
	SAIDI	17.747	92.2	92.306	59.6
	ENS+	0.829	92.3	9.117	52.1
100%	SAIFI	17.119	92.2	88.131	59.6
	SAIDI	19.781	91.4	93.601	59.1
	ENS+	0.894	91.7	9.179	51.8

Table 8 shows the resulting SAIFI, SAIDI, and ENS reliability indices for the LPM and F1 feeder, and Fig. 11 its graphical representation. Thus, introducing a hybrid

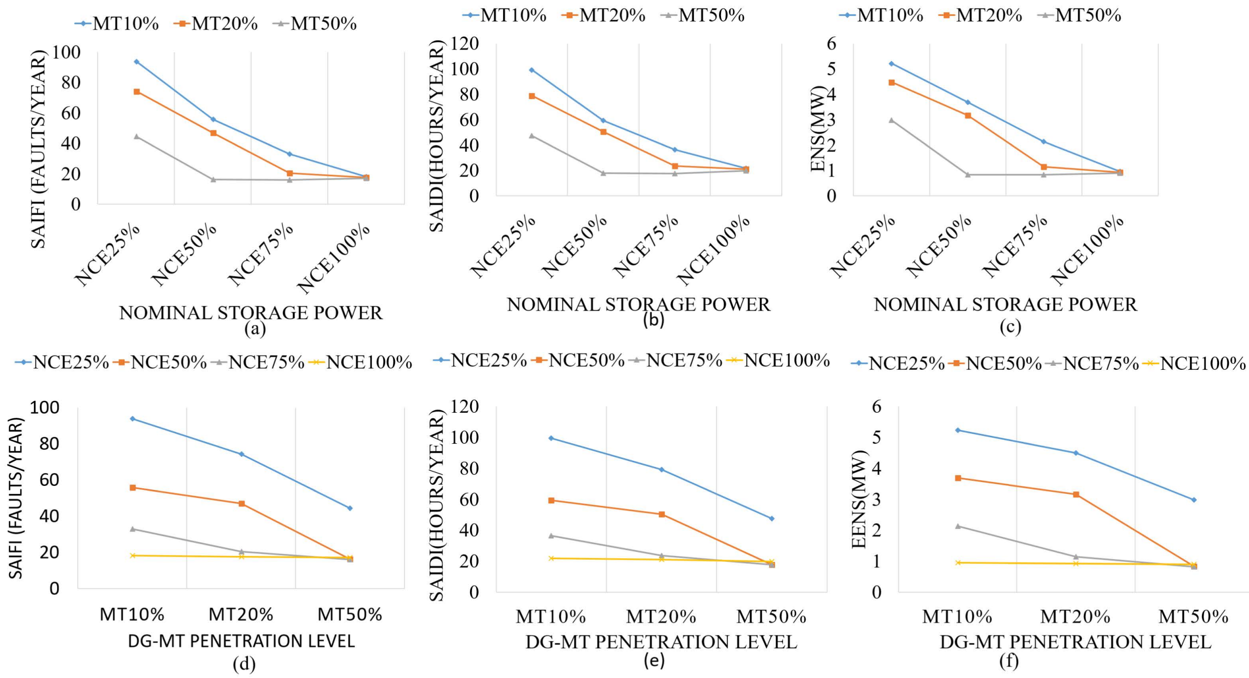

FIGURE 11. Reliability indices for the LPM varying the (a)–(c) NCE and (d)–(f) DG-MT penetration level in the modified RDS when DG-PV = 100%, ESC = 100% and MSC = 10%.

MG system combining different types of DG to the RDS dramatically increases its reliability. On the other hand, the reliability indices obtained via SMCS can be used to recommend a DG penetration level that meets a specific reliability objective. For example, when a DG-PV penetration level of 100% of the peak load, an ESC of 100% of the peak load, a MSC of 10% of the ESC, and a NCE of 25% are used, none of the reliability objectives (Table 7) can be achieved regardless of the DG-MT penetration levels. On the other hand, leaving DG-PV, ESC, and MSC fixed, and using a NCE of 50% allows achieving the reliability objectives with a DG-MT penetration level of 50%. A similar outcome is observed when DG-PV, ESC, and MCS are fixed, a NCE of 75% is used and the DG-MT penetration is set to 20% of the peak load. Similarly, by fixing DG-PV, ESC, and MSC, and setting NCE to 100%, the reliability objectives are achieved with a DG-MT penetration level of 10% of the peak load.

Other combinations for achieving the reliability objectives include fixing DG-PV, ESC, and MSC, setting a DG-MT penetration level of 50% of the peak load and that the ESS has a NCE of 50% of the ESC. However, if the DG-MT penetration level decreases to 20% of the peak load, the ESS would be required to have a NCE of 75% of the ESC. Finally, if the DG-MT penetration level was only 10% of the peak load, the ESS would need to have a NCE of 100% of the ESC.

V. CONCLUSION AND FUTURE WORK

In this document we evaluated the effect of introducing microgrids (MGs) for improving the reliability of rural distribution systems (RDS) using the Sequential Monte Carlo simulation (SMCS) method. In addition, we explored different penetration levels of renewable DGs such as DG-PV, the penetration levels of conventional DGs such as DG-MTs and ESS, while assessing the effect of different NCE levels.

Although we used a Colombian RDS as a case study, our approach can be generalized to other RDS in developing countries. By using different scenarios, we were able to show how the results of a reliability evaluation serve to recommend the sizing of the different systems comprising the MGs, with the ultimate goal of meeting specific reliability objectives. The study verified that introducing DG-PV alone would not achieve the reliability objectives set for the country of the case study, suggesting the need to introduce hybrid MGs and emphasizing the correct dimensioning of the penetration level of renewable DGs, non-renewable DGs and the NCE of the ESS. This result shows that the approach of the modeling and solution method is useful to assess the reliability of a complex system but also provides a tool to design it. Future research could combine the results of this study with technical and economic studies to determine the best solution that meets certain reliability objectives.

REFERENCES

[1] F. P. Marcos, C. M. Domingo, T. G. S. Román, and R. Cossent Arín, "Location and sizing of micro-grids to improve continuity of supply in radial distribution networks," *Energies*, vol. 13, no. 13, p. 3495, Jul. 2020.

[2] S. D. S. P. Domiciliarios. (2017). *Diagnóstico de la Calidad del Servicio de Energía Eléctrica en Colombia 2016*. Informe Técnico. Recuperado de. [Online]. Available: http://www.celsia.com/Portals/0/Documentos/PDF/informe-calidad-del-servicio-2016-superservicios.pdf

[3] Y. Yoldaş, A. Önen, S. M. Muyeen, A. V. Vasilakos, and İ. Alan, "Enhancing smart grid with microgrids: Challenges and opportunities," *Renew. Sustain. Energy Rev.*, vol. 72, pp. 205–214, May 2017.
[4] R. H. Lasseter and P. Paigi, "Microgrid: A conceptual solution," in *Proc. IEEE 35th Annu. Power Electron. Specialists Conf. (PESC)*, vol. 6, Jun. 2004, pp. 4285–4290.
[5] P. M. de Quevedo, J. Contreras, A. Mazza, G. Chicco, and R. Porumb, "Modeling and reliability assessment of microgrids including renewable distributed generation," in *Proc. IEEE 16th Int. Conf. Environ. Electr. Eng. (EEEIC)*, Jun. 2016, pp. 1–6.
[6] R. H. Lasseter, "Smart distribution: Coupled microgrids," *Proc. IEEE*, vol. 99, no. 6, pp. 1074–1082, Jun. 2011.
[7] M. Smith and D. Ton, "Key connections: The U.S. department of energy's microgrid initiative," *IEEE Power Energy Mag.*, vol. 11, no. 4, pp. 22–27, Jul. 2013.
[8] Q. Li, Z. Xu, and L. Yang, "Recent advancements on the development of microgrids," *J. Modern Power Syst. Clean Energy*, vol. 2, no. 3, pp. 206–211, Sep. 2014.
[9] M. Soshinskaya, W. H. J. Crijns-Graus, J. M. Guerrero, and J. C. Vasquez, "Microgrids: Experiences, barriers and success factors," *Renew. Sustain. Energy Rev.*, vol. 40, pp. 659–672, Dec. 2014.
[10] L. Wu, T. Ortmeyer, and J. Li, "The community microgrid distribution system of the future," *Electr. J.*, vol. 29, no. 10, pp. 16–21, Dec. 2016.
[11] R. Sabzehgar, "A review of AC/DC microgrid-developments, technologies, and challenges," in *Proc. IEEE Green Energy Syst. Conf. (IGESC)*, Nov. 2015, pp. 11–17.
[12] M. E. Khodayar, M. Barati, and M. Shahidehpour, "Integration of high reliability distribution system in microgrid operation," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1997–2006, Dec. 2012.
[13] N. Nikmehr and S. N. Ravadanegh, "Reliability evaluation of multi-microgrids considering optimal operation of small scale energy zones under load-generation uncertainties," *Int. J. Elect. Power Energy Syst.*, vol. 78, pp. 80–87, Jun. 2016.
[14] J. L. López-Prado, J. I. Vélez, and G. A. Garcia-Llinás, "Reliability evaluation in distribution networks with microgrids: Review and classification of the literature," *Energies*, vol. 13, no. 23, p. 6189, Nov. 2020.
[15] X. Liu, Y. Wang, C. Song, and H. Qu, "Reliability assessment of micro-grid based on Markov model," in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Oct. 2016, pp. 2434–2437.
[16] S. Guocheng, Z. Jingtao, Z. Xiaoyan, L. Cheng, Z. Yusen, K. Xiangyu, and L. Xinpeng, "Reliability analysis method for microgrid with intermittent distributed generations," in *Proc. China Int. Conf. Electr. Distrib. (CICED)*, Aug. 2016, pp. 1–5.
[17] M. Al-Muhaini, A. Bizrah, G. Heydt, and M. Khalid, "Impact of wind speed modelling on the predictive reliability assessment of wind-based microgrids," *IET Renew. Power Gener.*, vol. 13, no. 15, pp. 2947–2956, Nov. 2019.
[18] X. Chen, B. Liu, and C. Li, "A reliability evaluation method for distribution system with microgrids," in *Proc. Asia–Pacific Power Energy Eng. Conf.*, Mar. 2012, pp. 1–4.
[19] J. Faulin, A. A. Juan, S. S. M. Alsina, and J. E. Ramirez-Marquez, *Simulation Methods for Reliability and Availability of Complex Systems*. New York, NY, USA: Springer, 2010, ch. 7, pp. 145–171.
[20] S. Conti, S. A. Rizzo, E. F. El-Saadany, M. Essam, and Y. M. Atwa, "Reliability assessment of distribution systems considering telecontrolled switches and microgrids," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 598–607, Mar. 2014.
[21] B. Maleki, M. Gandomkar, T. Maleki, and F. H. Gandoman, "Method of evaluating reliability of microgrids in island mode by using load prioritization," in *Proc. 19th Conf. Electr. Power Distrib. Netw. (EPDC)*, May 2014, pp. 76–81.
[22] W. Zhong, L. Wang, Z. Liu, and S. Hou, "Reliability evaluation and improvement of islanded microgrid considering operation failures of power electronic equipment," *J. Modern Power Syst. Clean Energy*, vol. 8, no. 1, pp. 111–123, 2020.
[23] A. Ahadi, S. E. Reza, and X. Liang, "Probabilistic reliability evaluation for power systems with high penetration of renewable power generation," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2017, pp. 464–468.
[24] C. L. T. Borges and M. Costa, "Reliability assessment of microgrids with renewable generation by an hybrid model," in *Proc. IEEE Eindhoven PowerTech*, Jun. 2015, pp. 1–6.
[25] T. Tuffaha and M. AlMuhaini, "Reliability assessment of a microgrid distribution system with pv and storage," in *Proc. Int. Symp. Smart Electric Distrib. Syst. Technol. (EDST)*, Sep. 2015, pp. 195–199.
[26] T. Fan, S. Du, K. Liu, J. Su, and Y. Liu, "Reliability evaluation based on Monte Carlo simulation considering islanded operation in distribution network with microgrid," Beijing, China, 2015. [Online]. Available: https://digital-library.theiet.org/content/conferences/10.1049/cp.2015.0377
[27] H. Liang, J. Su, and S. Liu, "Reliability evaluation of distribution system containing microgrid," in *Proc. CICED*, Sep. 2010, pp. 1–7.
[28] R. Pinto, S. Mariano, M. Calado, and J. de Souza, "Impact of rural grid-connected photovoltaic generation systems on power quality," *Energies*, vol. 9, no. 9, p. 739, Sep. 2016.
[29] A. Kumar, A. R. Singh, Y. Deng, X. He, P. Kumar, and R. C. Bansal, "Integrated assessment of a sustainable microgrid for a remote village in hilly region," *Energy Convers. Manage.*, vol. 180, pp. 442–472, Jan. 2019.
[30] A. López-González, B. Domenech, and L. Ferrer-Martí, "Sustainability and design assessment of rural hybrid microgrids in Venezuela," *Energy*, vol. 159, pp. 229–242, 2018, doi: 10.1016/j.energy.2018.06.165.
[31] S. Uski, E. Rinne, and J. Sarsama, "Microgrid as a cost-effective alternative to rural network underground cabling for adequate reliability," *Energies*, vol. 11, no. 8, p. 1978, Jul. 2018.
[32] S. Uski, K. Forssén, and J. Shemeikka, "Sensitivity assessment of microgrid investment options to guarantee reliability of power supply in rural networks as an alternative to underground cabling," *Energies*, vol. 11, no. 10, p. 2831, Oct. 2018.
[33] M. Gunasekaran, H. M. Ismail, B. Chokkalingam, L. Mihet-Popa, and S. Padmanaban, "Energy management strategy for rural Communities' DC micro grid power system structure with maximum penetration of renewable energy sources," *Appl. Sci.*, vol. 8, no. 4, p. 585, Apr. 2018.
[34] S. Numminen, P. D. Lund, S. Yoon, and J. Urpelainen, "Power availability and reliability of solar pico-grids in rural areas: A case study from northern India," *Sustain. Energy Technol. Assessments*, vol. 29, pp. 147–154, Oct. 2018.
[35] N. Narayan, A. Chamseddine, V. Vega-Garita, Z. Qin, J. Popovic-Gerber, P. Bauer, and M. Zeman, "Quantifying the benefits of a solar home system-based DC microgrid for rural electrification," *Energies*, vol. 12, no. 5, p. 938, Mar. 2019.
[36] M. Y. Wu, M. I. Ridzuan, and S. Z. Djokic, "Smart grid functionalities for improving reliability of rural electricity networks," in *Proc. Medit. Conf. Power Gener., Transmiss., Distrib. Energy Convers. (MedPower)*, 2016, pp. 1–7, doi: 10.1049/cp.2016.1036.
[37] D. Elmakias, *New Computational Methods in Power System Reliability*. Berlin, Germany: Springer, 2008, ch. 3, pp. 171–230.
[38] R. Billinton and R. N. Allan, *Reliability Evaluation of Power Systems*, 2nd ed. New York, NY, USA: Plenum, 1994, ch. 7, pp. 220–247.
[39] R. Billinton and R. N. Allan, *Reliability Evaluation of Engineering Systems-Concepts and Techniques*. New York, NY, USA: Plenum Press, 1992.
[40] A. A. Alkuhayli, S. Raghavan, and B. H. Chowdhury, "Reliability evaluation of distribution systems containing renewable distributed generations," in *Proc. North Amer. Power Symp. (NAPS)*, Sep. 2012, pp. 1–6.
[41] A. Yahaya and M. AlMuhaini, "Reliability assessment of load points including solar and wind DGs," in *Proc. Int. Symp. Smart Electr. Distrib. Syst. Technol. (EDST)*, Sep. 2015, pp. 200–205.
[42] R. Billington and W. Li, *Reliability Assessment of Electric Power Systems Using Monte Carlo Methods*. New York, NY, USA: Springer, 1994, ch. 3, pp. 33–72.
[43] A. Abul'Wafa and A. Taha, "Reliability evaluation of distribution systems under μ grid-tied and islanded μ grid modes using Monte Carlo simulation," *Smart Grid Renew. Energy*, vol. 5, pp. 52–s62, 2014, doi: 10.4236/sgre.2014.53006.
[44] M. Tanrioven, "Reliability and cost–benefits of adding alternate power sources to an independent micro-grid community," *J. Power Sources*, vol. 150, pp. 136–149, Oct. 2005.
[45] M. Ansarian, S. M. Sadeghzadeh, and M. Fotuhi-Firuzabad, "Optimum generation dispatching of distributed resources in smart grids," *Int. Trans. Electr. Energy Syst.*, vol. 25, no. 7, pp. 1297–1318, Jul. 2015.
[46] A. Ahadi, N. Ghadimi, and D. Mirabbasi, "Reliability assessment for components of large scale photovoltaic systems," *J. Power Sources*, vol. 264, pp. 211–219, Oct. 2014.
[47] S. M. Nosratabadi, R.-A. Hooshmand, E. Gholipour, and S. Rahimi, "Modeling and simulation of long term stochastic assessment in industrial microgrids proficiency considering renewable resources and load growth," *Simul. Model. Pract. Theory*, vol. 75, pp. 77–95, Jun. 2017.
[48] G. Celli, E. Ghiani, F. Pilo, and G. G. Soma, "Reliability assessment in smart distribution networks," *Electr. Power Syst. Res.*, vol. 104, pp. 164–175, Nov. 2013.

[49] H. Lei and C. Singh, ''Non-sequential Monte Carlo simulation for cyber-induced dependent failures in composite power system reliability evaluation,'' *IEEE Trans. Power Syst.*, vol. 32, no. 2, pp. 1064–1072, May 2017.
[50] *Proyección Regional de la Demanda de Energía Eléctrica y Potencia Máxima en Colombia*, Unidad de Planeación Minero-Energética, Bogotá, Colombia, 2019.
[51] *Criterios de Diseño de la Red de Electrificación Rural*, Electrificadora de Santander, Bucaramanga, Colombia, 2019.
[52] *Indicadores de Calidad para la Continuidad en la Prestación del Servicio de Energía Eléctrica en Sistemas de Transmisión Regional Y/O Distribución Local CREG-069*, Comisión de Regulación de Energía y Gas, Bogotá, Colombia, 2004.
[53] R. N. Allan, R. Billinton, I. Sjarief, L. Goel, and K. S. So, ''A reliability test system for educational purposes-basic distribution system data and results,'' *IEEE Trans. Power Syst.*, vol. 6, no. 2, pp. 813–820, May 1991.
[54] R. E. Brown, *Electric Power Distribution Reliability*. Boca Raton, FL, USA: CRC Press, 2017.
[55] *Distribución de Energía Eléctrica Metodología de Remuneración 2018–2020 CREG-010*, Comisión de Regulación de Energía y Gas, Bogotá, Colombia, 2018.

JOSE L. LÓPEZ-PRADO received the B.S. degree in electronic engineering and the M.Sc. degree in industrial controls from Pamplona University, Colombia, in 2006 and 2010, respectively. He is currently pursuing the Ph.D. degree with the Universidad del Norte, Colombia.

He is currently an Assistant Professor with the Department of Electronic Engineering, University of Sucre, Colombia. His research interests include reliability assessment in microgrids, renewable energy, and power electronics.

JORGE W. GONZÁLEZ-SÁNCHEZ (Senior Member, IEEE) received the Electrical Engineering, M.Sc., and Ph.D. degrees in electrical engineering from UPB Colombia. He is currently a Professor with the Faculty of UPB Colombia. Formerly, he was with HMV Consulting, Siemens PTD Germany, and for Utility EPM. He was a Researcher with University Kempten, and the Power Systems Institute, Erlangen University, Germany. His research interests include protective relaying, optimization, power systems, HVDC, FACTS, substations. and renewable energies.

JORGE I. VÉLEZ was born in Medellín, Colombia. He received the B.S. degree in industrial engineering and the M.Sc. degree in statistics from the National University of Colombia, Medellín, in 2005 and 2008, respectively, and the Ph.D. degree in medical sciences (genomics and precision medicine) from Australian National University, Canberra, ACT, Australia, in 2016.

Currently, he is an Assistant Professor with the Department of Industrial Engineering, Universidad del Norte, Barranquilla. His research interests include the development and application of bioinformatics, machine learning, and statistical genetic models/tools that lead to a better understanding of the aetiology of complex human diseases and the identification of key genetic factors that confer susceptibility to ADHD, alzheimer's disease (AD), and cancer. His areas of expertise include data science/analytics, bioinformatics, predictive and population genetics, genetic epidemiology, computational statistics, and genetics. In 2020, he was a recipient of the Scientific Merit Medal from the Universidad del Norte for his important work in the field of research and science with national and international recognition.

GUISSELLE A. GARCIA-LLINÁS was born in Barranquilla, Colombia. She received the B.S. degree in industrial engineering from the Universidad del Norte, Colombia, in 2003, the M.Sc. degree in industrial engineering from the Universidad de Los Andes, Colombia, in 2005, and the M.Sc. degree in engineering and the Ph.D. degree in industrial engineering from The State University of New York at Buffalo, USA, in 2011 and 2013, respectively. Currently, she is an Assistant Professor with the Department of Industrial Engineering, Universidad del Norte, entrusted with administrative duties as the Coordinator of the Master and Ph.D. programs in industrial engineering. Her research interests include mathematical modeling, optimization, network flows, complex systems, and resilience with applications in manufacturing, urban design, agro-industry, energy, and transportation.