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Reliability Assessment of Energy Limited Systems Using Sequential Montecarlo Simulation

C. J. Zapata, *Member, IEEE*, L. P. Garcés, and O. Gómez

***Abstract*— This paper explains why the reliability assessment of energy limited systems requires more detailed models for primary generating resources availability, internal and external generating dispatch and customer demand than the ones commonly used for large power systems and presents a methodology based on the full sequential Montecarlo simulation technique with AC power flow for their long term reliability assessment which can properly include these detailed models. By means of a real example, it is shown how the simplified modeling traditionally used for large power systems leads to pessimistic predictions if it is applied to an energy limited system and also that it cannot predict all the load point adequacy problems.**

***Index Terms*--Interconnected power system, power system reliability, power system simulation.**

I. Introduction

POWER systems with uncertainty on the availability of primary generating resources are called "energy limited systems" [1]. This situation arises when:

- There is no thermal generation or installed thermal capacity has a low participation.
- Hydraulic generation has not large reservoirs.
- An important portion of installed generating capacity operates with non-storable energy resources such as sun or wind.

Thus, energy limited systems depend on the support of other systems to cover their demand. However, in many cases, this support has also uncertainty due to:

- Transport restraints between the supporting systems and the supported one due to random failures that affects the availability of transmission equipment or poor operative conditions such as overloads, low voltage regulation, etc.
- Energy limitation in the supporting systems.

Energy limited systems with uncertainty on the support given by other systems are very common in many developing countries due to the lack of resources for investment in new generation and transmission facilities.

The uncertainty on the availability of primary energy resources for internal generating plants and on the external support makes the study of these systems a special problem where the simplifications commonly used for large power systems do not apply.

Using the power system that serves the city of Pereira in Colombia as example, this paper explains how to model primary generating resources availability, internal and external generating dispatch and customer demand of energy limited systems and presents a methodology based on the full sequential Montecarlo simulation technique with AC power flow for their long term reliability assessment.

II. System Description

The system under study is shown in Fig. 1. It serves approximately 115,000 customers with a forecasted demand of 103 MW for year 2006.

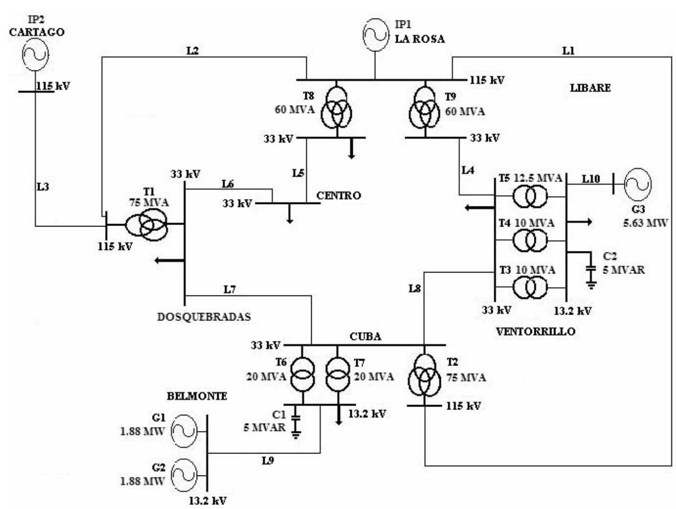

Fig. 1. Composite power system of Pereira

There are two interconnecting points (IP) to neighboring systems. The support of these systems is always required because the installed capacity is lower than the maximum demand.

All generating plants are run of the river type and they all are fed by Otún River.

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III. Modeling

A. Generation Dispatch

1) Internal generation

The dispatch of any generating unit depends on two independent aspects:

- Unit availability
- Primary energy resources availability.

In the case of fossil-fueled generation or hydraulic generation with large reservoirs it can be assumed for the long term totally certainty on the availability of the primary generating resources, i. e. the generating dispatch can be performed considering all required generating resources are always available. Thus, only the availability of the units is modeled, for example, by means of capacity outage tables [6], [11]. However, for wind, sun or hydraulic generation without large reservoirs, it is necessary to model both aspects unit availability and the variables which represent the availability of primary energy resources.

For the system under study, the river flow q is modeled by means of a Gaussian distribution with parameters μ=11.6213 m^3/s (mean) and σ = 6.0370 m^3/s (deviation). This model was built using records of average monthly river flow in a period of 19 years [14]. The available water flow to generate q_G in m^3/s is the river flow q minus an environmental restraint q_{ER} (1.5 m^3/s). For Libaré Plant, also applies a restraint q_{AQ} (2.6 m^3/s), the water flow for the city aqueduct. Thus:

$$q_G = q - q_{ER} - q_{AQ} \tag{1}$$

The available active power to dispatch in kW is given by:

$$P_{BELMONTE} = 916.3 * q_G \tag{2}$$

$$0.5 \leq q_G \leq 1.855 \tag{3}$$

$$P_{LIBARE} = 736.372 * q_G \tag{4}$$

$$0.5 \leq q_G \leq 6.79 \tag{5}$$

Equations (2), (4) refer to each generating unit. Constraints (3), (5) refer to minimum and maximum unit flow intake.

Generator capability curves are used for reactive dispatch.

2) External generation

Neighboring systems can supply at any time the difference between system demand and available internal generation. However, how this required power P_R is imported by the IP's is unknown because the power quantities available at each IP depend on the following random aspects:

- Generation dispatch: In the Colombian Energy Market, generating units greater than 20 MW are hourly dispatched in ascending order of bid price [1]. This determines the location inside the supporting systems of dispatched generation and the quantity of power that can be effectively dispatched to each IP of the supported system.
- Transmission availability: Unplanned outages (failures, vandalism, accidents, etc.) that affects transmission equipment and poor operational conditions (overloads, low voltage regulation, etc.) limit the quantity of power that can be effectively transported to each IP of the supported system.

The amount of power imported by each IP has important effect on the electrical performance of the supported system.

The model of external generation dispatch considers that P_R can be supplied by any IP with equal probability. Thus, if U is a random number uniformly distributed, then:

$$P_{IP1} = P_R * U \tag{6}$$

IP2 supplies the required external power not imported by IP1.

B. Demand

Load point active and reactive hourly curves for two typical days (ordinary & holiday) are used to properly include demand variation by hour and type of day, power factor variation and demand diversity. Other types of days should be defined if other aspects, for example seasons, have important effect on demand.

Demand curves are obtained from previous years demand records. Steps are:

1. Load point hourly demand (active, reactive) on a given typical day (ordinary, holiday) is the average of records for that hour in all similar days in a previous year.
2. System hourly demand curves (active, reactive) on a given typical day (ordinary, holiday) are obtained adding the corresponding curves of all load points. Thus, system maximum active demand for a previous year is obtained.
3. Load point demand curves obtained in step 1 are expressed in per unit of system maximum active demand simply dividing their hourly values by system maximum active demand obtained in step 2.

The per unit demand curves of each load point are used for any future year of study simply multiplying their values by the forecasted system maximum active demand for that year.

C. Component Modeling for Load Flow

Classical modeling of power system components for load flow studies is used i. e, positive sequence impedances and admittances.

D. Component Modeling for Reliability Assessment

Montecarlo simulation can include multi-state component reliability models defined by means of any kind of probability distribution, not only the exponential one as in other methods.

For the system under study, all system components are modeled by means of the classical two-state probability model which considers a component has only two states: "available" and "unavailable" ("up" and "down").

The transitions between these operative states are defined by means of the probability distributions of time to outage (tto) and time to restoration (ttr).

The component reliability models for the system under study are shown in Table I. These distributions were obtained using records of planned and unplanned outages and their corresponding restorations in a period of approximately five years (Jul 1998-Jun 2003) [5], [14].

TABLE I
PROBABILITY DISTRIBUTIONS FOR COMPONENT MODELING

	Time to outage			Time to restoration		
		Parameters			Parameters	
		α	β		α	β
L1	Weibull	0.2772	0.5186	Weibull	3.2507	0.4693
L2	Weibull	0.0807	0.6577	Weibull	5.0019	0.7500
L3	Lognormal	3.0728	1.7674	Lognormal	-3.5368	1.6550
L4	Weibull	0.2258	0.6839	Lognormal	-4.2188	1.6663
L5	Weibull	0.2116	0.6315	Lognormal	-4.3222	1.6048
L6	Weibull	0.1635	0.5810	Lognormal	-3.5156	1.7853
L7	Weibull	0.3126	0.5244	Lognormal	-2.9320	2.1986
L8	Weibull	0.2727	0.6354	Weibull	2.0918	0.4468
L9	Weibull	0.2052	0.6864	Lognormal	-4.3879	1.4371
L10	Weibull	0.1357	0.7269	Lognormal	-4.8468	1.4617
T1	Lognormal	2.7903	1.9180	Lognormal	-3.0151	1.9775
T2	Lognormal	3.8764	2.1516	Lognormal	-2.9028	1.8377
T3	Weibull	0.1009	0.5892	Lognormal	-4.3204	1.8035
T4	Weibull	0.0981	0.5904	Lognormal	-4.2656	1.6625
T5	Weibull	0.0661	0.6498	Lognormal	-3.9470	1.6431
T6	Lognormal	2.5897	2.1240	Lognormal	-3.7845	1.8459
T7	Lognormal	2.5549	2.0906	Weibull	6.7162	0.5902
T8	Lognormal	2.7903	1.9180	Lognormal	-3.0151	1.9775
T9	Lognormal	2.7903	1.9180	Lognormal	-3.0151	1.9775
G1	Weibull	0.4393	0.6237	Lognormal	-1.5504	1.8280
G2	Weibull	0.3928	0.7417	Lognormal	-1.4351	1.9360
G3	Weibull	0.4957	0.6563	Lognormal	-1.3516	2.0472
BF	Weibull	0.2752	0.7141	Lognormal	-2.1042	1.1568

Notes:
1. Equations of probability distributions are shown in Appendix B.
2. Time units are days.

It is important to observe that none of the component models in Table I is defined by means of the exponential distribution. All these models include terminal equipment.

The civil/hydraulic facilities of Belmonte plant are modeled as an independent component (BF) because an outage on it implies a common mode outage on both units.

IV. PROCEDURE OF THE SIMULATION

The system performance in a future year of interest is observed artificially by means of the Montecarlo simulation. The study is performed for several scenarios defined by system topology, expansion/upgrading, forecasted demand, component loss criteria (*n-1*, *n-2*), etc. As the load model is hourly, this kind of simulation is "full sequential" [3].

As it is shown in Fig. 2, a simulation consists of N iterations or artificial observations of one year of system operation under the conditions specified by a given scenario.

Within iterations, the sequence of component outages and restorations is generated. The x's in Fig. 2, indicate the periods of system operation with loss of components.

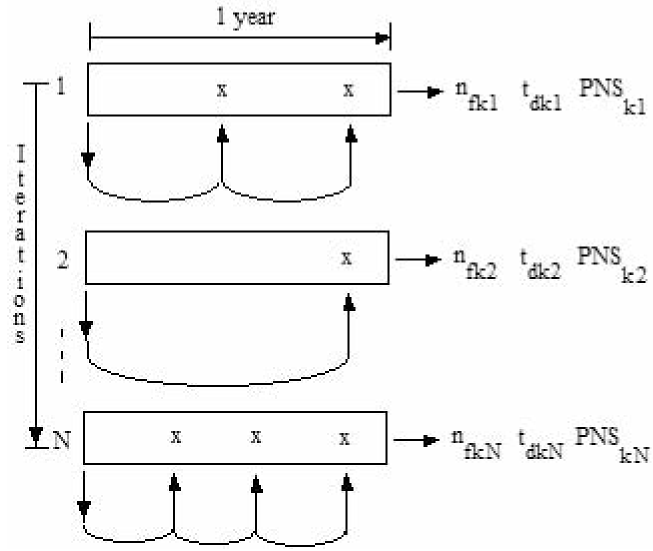

Fig. 2. Simulation procedure

The system electrical performance is assessed by means of AC load flow only during the x's. If there are abnormal operative conditions such as component overloads or voltage out of limits, some remedial actions are taken:

- Load shedding
- Adjust reactive compensation

Other corrective actions can also be implemented in accordance to the system under study.

The flow chart in Fig. 3 presents in detail the procedure within iterations [2], [3], [14].

There will be a "failure" on a load point if [1]:

- It is isolated, or
- Load curtailment is applied, or
- There are voltage violations ($0.95 \leq V_{p.u.} \leq 1.05$).

For a load point k the samples of output variables such as number of failures n_{fk}, down time t_{dk} and power no served PNS_k allow the calculation of reliability indexes; for example:

- Expected Failure Frequency

$$\lambda_k = \sum_{i=1}^{N} n_{fki} / N \quad (7)$$

- Expected Unavailability

$$U_k = \sum_{i=1}^{N} t_{dki} / N \quad (8)$$

- Expected Load Not Served (Load Curtailed)

$$EPNS_k = \sum_{i=1}^{N} PNS_{ki} / N \quad (9)$$

Two stopping rules are used for the simulation: A fixed number of iterations and the coefficient of variation [2], [10] of the load point indexes.

The samples of the output variables can also be fitted to probability distributions and so the probabilistic models of the reliability indexes are obtained.

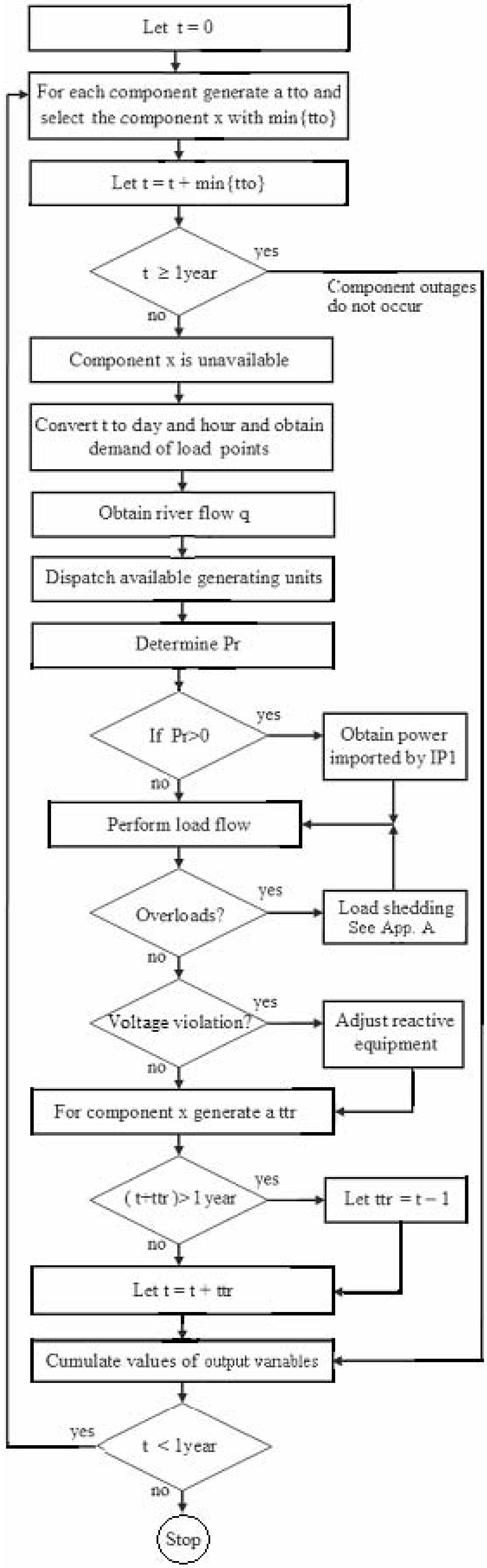

Fig. 3. Procedure within iterations

V. Example

Two cases are presented to illustrate the differences in results when using the detailed modeling of proposed methodology and those obtained when the simplified modeling commonly used for large power systems is applied to an energy limited system. See Table II.

TABLE II
CASES OF STUDY

	Case 1 Detailed modeling	Case 2 Simplified modeling
Load point demand	Hourly active and reactive curves for ordinary day and holiday	Active and reactive demand correspond to hour of maximum system demand (19:00) in an ordinary day
Internal generating Dispatch	Probabilistic model for water availability	Considers average water flow
External generating dispatch	Probabilistic model for imported amount by IP's	20% of *Pr* is imported by IP2

The scenario under study in both cases is year 2006 with a forecasted system maximum active demand of 103 MW, the same topology shown in Fig. 1 and $n-1$ loss of component criteria.

Tables III to VII show the results obtained with 1000 iterations. All per unit power values correspond to a 100 MVA base. The difference between results for a given reliability index I is calculated as:

$$\Delta\% = ((I_{CASE\,2} - I_{CASE1}) / I_{CASE1}) * 100\% \qquad (10)$$

As the reliability indexes are calculated for a future year or in the long-term, they are also called "adequacy indexes" and they all correspond to expected values.

TABLE III
RESULTS FOR FAILURE FREQUENCY [FAILURES/YEAR]

Load point	Case 1 Detailed modeling	Case 2 Simplified modeling	Δ%
Cuba 13.2 kV	8.6430	13.454	+55.66
Ventorillo 13.2 kV	34.490	91.108	+164.16
Ventorillo 33 kV	3.8730	4.2300	+9.22
Centro 33 kV	0.3210	0.5840	+81.93
La Rosa 33 kV	0.3340	0.5840	+74.85
Dosquebradas 33 kV	0.2760	0.5810	+110.51

TABLE IV
RESULTS FOR VOLTAGE VIOLATIONS [EVENTS/YEAR]

Load point	Case 1 Detailed modeling	Case 2 Simplified modeling	Δ%
Cuba 13.2 kV	6.8900	11.234	+63.05
Ventorillo 13.2 kV	33.7130	79.134	+134.73
Ventorillo 33 kV	3.8710	4.2300	+9.27
Centro 33 kV	0.3180	0.5840	+83.65
La Rosa 33 kV	0.3320	0.5840	+75.90
Dosquebradas 33 kV	0.2760	0.5810	+110.51

Note:
All voltage violations correspond to the lower limit

TABLE V
RESULTS FOR FAILURE DURATION [DAYS/YEAR]

Load point	Case 1 Detailed modeling	Case 2 Simplified modeling	Δ%
Cuba 13.2 kV	2.1450	2.1700	+1.166
Ventorillo 13.2 kV	169.0818	930.7031	+450.45
Ventorillo 33 kV	0.3452	0.4288	+24.22
Centro 33 kV	0.5521	0.2022	-63.38
La Rosa 33 kV	0.1188	0.2022	+70.20
Dosquebradas 33 kV	0.0669	0.2803	+318.98

TABLE VI
RESULTS FOR CURTAILED ACTIVE LOAD [MW/YEAR]

Load point	Case 1 Detailed modeling	Case 2 Simplified modeling	Δ%
Cuba 13.2 kV	9.69	30.10	+210.63
Ventorillo 13.2 kV	2.78	45.08	+1521.58
Ventorillo 33 kV	0.00	0.00	0.00
Centro 33 kV	0.03	0.00	-100.00
La Rosa 33 kV	0.01	0.00	-100.00
Dosquebradas 33 kV	0.04	0.00	-100.00

TABLE VII
RESULTS FOR CURTAILED REACTIVE LOAD [MVAR/YEAR]

Load point	Case 1 Detailed modeling	Case 2 Simplified modeling	Δ%
Cuba 13.2 kV	4.37	10.03	+129.52
Ventorillo 13.2 kV	1.49	23.69	+1489.93
Ventorillo 33 kV	0.00	0.00	0.00
Centro 33 kV	0.01	0.00	-100.00
La Rosa 33 kV	0.01	0.00	-100.00
Dosquebradas 33 kV	0.02	0.00	-100.00

VI. CONCLUSIONS

1. The sequential Montecarlo simulation is a powerful method for the reliability assessment of energy limited systems because it can easily include detailed models for primary generating resources availability, internal/external generating dispatch and customer demand. Additionally, operative actions such as load shedding, re-dispatch, reactive management and planning tools like optimization can also be incorporated.
2. The Montecarlo method allows the use of any kind of probability distribution for the modeling of the times to outage and times to restoration of the components, not only the exponential distribution as in other methods. Thus, with this method, aged components, which have increasing failure rate, and restoration times, which are generally normal o lognormal distributed, can be properly modeled.
3. A simplified modeling of primary generating resources availability, internal/external generating dispatch and customer demand leads to pessimistic predictions, i. e. higher expected values of the reliability indexes, if it is applied to the reliability assessment of an energy limited system. Also, it cannot predict the adequacy problems of all load points.
4. Reliability assessments of energy limited systems with detailed modeling are more realistic because the high correlation between modeling and reality. Then, the risk of using their results in the decision making process will be lower.
5. If planners of energy limited systems want to exploit current systems to their maximum capacity and extend the use of system components beyond their useful life, a detailed modeling is required because the results obtained using a simplified one are more severe and could indicate the need of system upgrading or expansion that are really not necessary for the year under study or that can be postponed some years.

VII. ACKNOWLEDGMENT

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VIII. APPENDIX A – LOAD SHEDDING METHODOLOGY

Load shedding is not a simple problem due to non linearity nature of load flow. This problem has two parts: determination of best load points for load shedding and determination of the amount of load to be curtailed at these points.

A comprehensive solution for this problem requires the application of optimization techniques. An approximated approach was applied for software development which consists in the use of the ac power transfer distribution factors (PTDF) described in [4]. Steps are:

1. From a performed load flow, form the full Jacobian matrix [J] to include all the system buses except the slack bus and find its inverse $[J]^{-1}$.
2. For a load point k assume a negative change in demand of ΔS = 1 MVA.
3. Determine ΔP and ΔQ using the power factor *pf*:

$$\Delta P = -\Delta S * pf \tag{11}$$

$$\Delta Q = -\Delta S * pf \tag{12}$$

4. Compute the change in voltage angles and magnitudes:

$$\begin{pmatrix} \Delta\delta \\ \Delta V \end{pmatrix} = [J]^{-1} \begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} \tag{13}$$

5. Update the system voltages and compute for each transmission line i the change in transported active power P_{ti} and transmitted reactive power Q_{ti}.
6. Compute for each transmission line i the ac PTDF:

$$PTDF_{ik} = \Delta S_{ti} / \Delta S \tag{14}$$

7. Repeat steps 2 to 5 for all load points.

Finally, for every transmission line there is a set of PTDF, one for each load point. For a given transmission line, the load points which produce higher PTDF magnitudes are the more convenient for load shedding.

IX. APPENDIX B - PROBABILITY DENSITY FUNCTIONS

- Gaussian

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} * e^{-(x-\mu)^2/2\sigma^2} \quad (15)$$

- Weibull

$$f(x) = \alpha\beta(x^{\beta-1}) * e^{-\alpha x^{\beta}} \quad (16)$$

- Lognormal

$$f(x) = \frac{1}{x\beta\sqrt{2\pi}} * e^{-(\ln(x)-\alpha)^2/2\beta^2} \quad (17)$$

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XI. BIOGRAPHIES

Carlos J. Zapata (SM'1993, AM'1997, M'2004) was born in Cartago, Colombia, on January 25, 1966. He obtained his BScEE from Universidad Tecnológica de Pereira, Pereira, in 1991 and his MScEE from Universidad de Los Andes, Bogotá, in 1996. From 1991 to 2001 he worked for Consultoría Colombiana S. A, Bogotá, Colombia, where he participated in forty one projects in the areas of power system studies, electrical designs and software development; He was Project Manager in fifteen of these projects. In 2001, he joined Universidad Tecnológica de Pereira.

Lina P. Garcés was born in San Pelayo, Colombia, on November 11, 1980. She obtained her BScEE and MScEE from Universidad Tecnológica de Pereira, Pereira, in 2003 and 2005, respectively. She worked during 2003 and 2004 in the project "Reliability Study of Regional Electric Power System" and during 2005 in the project "Methodologies for reliability assessment in power distribution companies", both sponsored by the Research and Extension Center of Universidad Tecnológica de Pereira. Currently, she is working towards her PhD Universidade Estadual Paulista "Julio de Mesquita Filho", Ilha Solteira, Brazil.

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