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New methodology to diagnose reliability of a single distribution circuit in Colombia

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Abstract
A reliable electric power supply is of ever increasing importance in the Colombian electricity market. As such, the Energy and Gas Regulation Commission, (CREG for its acronym in Spanish), has contracted technical studies to be undertaken in order to assess reliability for Colombian electric utilities. This paper focuses on a new methodology to diagnose the reliability of a single distribution circuit that is to be used in Colombian electric utilities. The proposed methodology includes calculating known reliability indexes (SAIFI, SAIDI, CAIDI, etc.) as well as new reliability indexes in order to determine the incidence of causes of failure. This paper explains some of the required files´ characteristics (input and output files) in order to execute two applications associated with the previously mentioned methodology. These two applications were developed using Microsoft Excel for the Strategic Energy Business Unit at EMCALI EICE ESP, located on Santiago de Cali, Valle del Cauca, Colombia, South America. This article describes some features of these applications. The first case study presented, about the first application, is calculated based on this methodology, and results obtained are compared with those obtained using ETAP software. Finally, the second case study, regarding the second application, is calculated based on this methodology and results obtained are shown in this document.

Keywords: Assess reliability; Colombian electric utilities; methodology; diagnose the reliability; single distribution circuit; reliability indexes; causes of failure; files; applications; Microsoft Excel; EMCALI EICE ESP; case study; ETAP software.

Nueva metodología para el diagnóstico de la confiabilidad de un circuito individual de distribución en Colombia

Resumen
El suministro confiable de energía eléctrica es cada vez más importante en el mercado eléctrico colombiano. De esta manera, la Comisión de Regulación de Energía y Gas, (CREG por su sigla en español), ha contratado estudios técnicos a ser llevados a cabo a fin de evaluar la confiabilidad de las empresas del sector eléctrico colombiano. Este trabajo se enfoca en una nueva metodología para diagnosticar la confiabilidad de un circuito individual de distribución a ser utilizado en las empresas del sector eléctrico colombiano. La metodología propuesta incluye el cálculo de índices de confiabilidad conocidos (SAIFI, SAIDI, CAIDI, etc.), así como nuevos índices de confiabilidad con el fin de determinar la incidencia de las causas de falla. Este documento explica algunas características de los archivos requeridos (archivos de entrada y salida) con el fin de ejecutar dos aplicaciones asociadas con la metodología mencionada anteriormente. Estas dos aplicaciones fueron desarrolladas utilizando Microsoft Excel para la Unidad Estratégica de Negocio de Energía de EMCALI EICE ESP, localizada en Santiago de Cali, Valle del Cauca, Colombia, Sudamérica. Este artículo describe algunas características de estas aplicaciones. El primer caso de estudio presentado, sobre la primera aplicación, se calcula sobre la base de esta metodología y los resultados obtenidos se comparan con aquellos obtenidos utilizando el software ETAP. Por último, el segundo caso de estudio, con respecto a la segunda aplicación, se calcula sobre la base de esta metodología y los resultados obtenidos se muestran en este documento.

Palabras clave: Evaluar la confiabilidad; empresas del sector eléctrico colombiano; metodología; diagnosticar la confiabilidad; circuito individual de distribución; índices de confiabilidad; causas de falla; archivos; aplicaciones; Microsoft Excel; EMCALI EICE ESP; caso de estudio; software ETAP.

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1. Introduction

The two approaches to reliability assessment of electrical power systems are historical evaluation and predictive evaluation. Historical reliability evaluation involves the collection and analysis of an electric system's outage and interruption data.

Predictive evaluation determines the long-term behavior of systems by combining component failure rates and the duration of repair, restoration, and switching and isolation activities that describe the tendency of an entire utility's distribution system for given network configurations [1,2].

The Energy and Gas Regulation Commission, (CREG for its acronym in Spanish), has contracted technical studies to be undertaken regarding historical reliability assessment. The SAIFI and SAIDI indexes per each electric utility have been calculated in these studies [3]. Colombian electric utilities require a methodology to be used, which allow a reliability diagnosis to be performed from a historical assessment point of view. It is necessary to start with a historical reliability assessment in order to later continue with predictive reliability assessment. In terms of the Colombian electricity market, a good starting point is a methodology that allows for a reliability diagnosis to be undertaken of a single distribution circuit. Colombian electric utilities require a reliability diagnosis, which allows them to calculate known reliability indexes to measure the quality of service as well as new indexes to determine the incidence of causes of failure. It is also important to determine of the incidence of causes of failure as this allows the investments to be defined that are aimed at improving the reliability of distribution circuits [10-12].

2. Brief description of the methodology

Two applications were developed for the methodology using Microsoft Excel, which allowed the reliability diagnosis of a single distribution circuit to be performed. These applications are RELIABILITY-INDEXES-CALCULATION.xlsm and RELIABILITY-INPUT-DATA-AND-STATISTICS.xlsm. Initial information corresponds to causes.xls and circuit.xls files. RELIABILITY-INPUT-DATA-AND-STATISTICS.xlsm opens and processes these two files in order to generate two output files. The output files are RELIABILITY-INPUT-DATA.xls and RELIABILITY-STATISTICS.xls. This last file is used to show the values of new reliability indexes to determine the incidence of causes of failure. RELIABILITY-INPUT-DATA.xls is used to show the reliability input data required to calculate known reliability indexes. The known reliability indexes are SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index), CAIDI (Customer Average Interruption Duration Index), ASAI (Average Service Availability Index), ASUI (Average Service Unavailability Index), EENS (Expected Energy Not Supplied Index), ECOST (Expected Interruption Cost Index), AENS (Average Energy Not Supplied Index), and IEAR (System Interrupted Energy Assessment Rate Index) [4-6].

RELIABILITY-INPUT-DATA-AND-STATISTICS.xlsm calculates the reliability input data and the reliability statistics. The reliability input data are λ_A (active failure rate), λ_{PR} (passive failure rate on the primary line, the failures of which can be cleared using a recloser), λ_{PL} (passive failure rate on the primary line, the failures of which cannot be cleared by means of a recloser), λ_{PT} (passive failure rate of primary electrical equipment, which is composed of a transformer, fuses and a surge arrester), λ_{PS} (passive failure rate for the secondary network system), U_A (active outage duration), U_{PR} (passive outage duration on the primary line, the failures of which can be cleared by means of a recloser), U_{PL} (passive outage duration on the primary line, the failures of which cannot be cleared by means of a recloser), U_{PT} (passive outage duration for primary electrical equipment, which is composed of a transformer, fuses and a surge arrester), U_{PS} (passive outage duration for the secondary network system), $MONEY_i$, $ENERGY_i$, $IEAR_i$, N_i and P_i. Based on the above, the mathematical formulas associated with reliability input data and selected reliability indexes are as follows:

$$\lambda_i = \lambda_A + \lambda_{PL} + \lambda_{PR} + \lambda_{PT} + \lambda_{PS} \tag{1}$$

$$U_i = U_A + U_{PL} + U_{PR} + U_{PT} + U_{PS} \tag{2}$$

$$P_i = \frac{ENERGY_{AVERAGE-i}}{720} \tag{3}$$

$$EENS_i = P_i \; U_i \tag{4}$$

$$ECOST_i = P_i \, \Sigma \, f(r_j) \, \lambda_i \tag{5}$$

$$IEAR_i = \frac{MONEY_i}{ENERGY_i} \tag{6}$$

$$CCDF_i = \frac{(IEAR_i \;\; EENS_i)}{(P_i \;\; \lambda_i)} \tag{7}$$

$$ECOST_i = P_i \; CCDF_i \;\; \lambda_i \tag{8}$$

$$\text{SAIFI} = \frac{\Sigma(N_i \;\; \lambda_i)}{\Sigma N_i} \tag{9}$$

$$\text{SAIDI} = \frac{\Sigma(N_i \;\; U_i)}{\Sigma N_i} \tag{10}$$

$$\text{CAIDI} = \frac{\Sigma(N_i \;\; U_i)}{\Sigma(N_i \; \lambda_i)} \tag{11}$$

$$\text{ASAI} = \frac{[\,\Sigma(8760 \;\; N_i) - \Sigma(N_i \;\; U_i)]}{\Sigma(8760 \;\; N_i)} \tag{12}$$

$$\text{ASUI} = 1 - \text{ASAI} \tag{13}$$

$$\text{EENS} = \Sigma EENS_i \tag{14}$$

$$\text{ECOST} = \Sigma ECOST_i \tag{15}$$

$$\text{AENS} = \frac{EENS}{\Sigma N_i} \quad (16)$$

$$\text{IEAR} = \frac{ECOST}{EENS} \quad (17)$$

Where λ_i is the average failure rate at load point i, U_i is the annual outage duration at load point i, P_i is the average load of load point i, $ENERGY_{AVERAGE\text{-}i}$ is the average monthly active energy consumption in the last year at load point i, $EENS_i$ is the expected energy not supplied index at load point i, $ECOST_i$ is the expected interruption cost index at load point i, $f(r_j)$ is the CCDF (Composite Customer Damage Function) for element j, $IEAR_i$ is the interrupted energy assessment rate index at load point i, $MONEY_i$ is the last month´s sum of invoiced values for active energy consumed by customers connected to load point i, $ENERGY_i$ is the sum of energies consumed by customers over the last month connected to load point i, $CCDF_i$ is the CCDF at load point i, and N_i is the number of customers at load point i [7,8]. For Colombian electric utilities, a load point i is the same as a primary node with an associated load. The sum of invoiced values related to the $MONEY_i$ calculation is performed through the Unitary Cost per each customer according to Colombian electricity market regulations [9].

RELIABILITY-INPUT-DATA-AND-STATISTICS.xlsm also calculates new reliability indexes to determine incidence of causes of failure. These new reliability indexes are: λ_{PR}, λ_{PL}, λ_{PT}, λ_{PS}, U_{PR}, U_{PL}, U_{PT}, U_{PS}, $EENS_{cause}$ (expected energy not supplied index associated with the cause of failure), $ECOST_{cause}$ (expected interruption cost index associated with the cause of failure), $EENS_A$ (expected energy not supplied index associated with active failures), $EENS_{PL}$ (expected energy not supplied index associated with passive failures at the primary line, the failures of which cannot be cleared by means of a recloser), $EENS_{PR}$ (expected energy not supplied index associated with passive failures at the primary line, the failures of which can be cleared by means of a recloser), $EENS_{PT}$ (expected energy not supplied index associated with passive failures of primary electrical equipment, which is composed of a transformer, fuses and a surge arrester), $EENS_{PS}$ (expected energy not supplied index associated with passive failures at the secondary network system), $ECOST_A$ (expected interruption cost index associated with active failures), $ECOST_{PL}$ (expected interruption cost index associated with passive failures at the primary line, the failures of which cannot be cleared by means of a recloser), $ECOST_{PR}$ (expected interruption cost index associated with passive failures at the primary line, the failures of which can be cleared by means of a recloser), $ECOST_{PT}$ (expected interruption cost index associated with passive failures of primary electrical equipment, which is composed of a transformer, fuses and a surge arrester), $ECOST_{PS}$ (expected interruption cost index associated with passive failures at the secondary network system), and $\lambda_{cause\ per\ neighborhood}$ (average failure rate associated with the cause of failure in the given neighborhood). Thus, the missing mathematical formulas relating to the above mentioned indexes are as follows:

$$\lambda_{cause} = \frac{number\ of\ failures_{cause}}{period\ under\ analysis} \quad (18)$$

$$U_{cause} = \frac{duration\ of\ failures_{cause}}{period\ under\ analysis} \quad (19)$$

$$EENS_{cause} = \Sigma EENS_{causef} \quad (20)$$

$$ECOST_{cause} = \Sigma ECOST_{causef} \quad (21)$$

$$EENS_j = \Sigma EENS_{jf} \quad (22)$$

$$ECOST_j = \Sigma ECOST_{jf} \quad (23)$$

$$\lambda_{circuit} = \Sigma \lambda_{cause} = \Sigma \lambda_i \quad (24)$$

$$U_{circuit} = \Sigma U_{cause} = \Sigma U_i \quad (25)$$

$$\lambda_{neighborhood} = \Sigma \lambda_{cause\ per\ neighborhood} \quad (26)$$

Where λ_{cause} is the average failure rate associated with the cause of failure, number of $failures_{cause}$ is the number of valid failure records that the given cause of failure presents, duration of $failures_{cause}$ is the sum of durations of valid failure records that the given cause of failure presents, period under analysis is the time period measured in years for which the reliability diagnosis is performed, U_{cause} is the annual outage duration associated with the cause of failure, $EENS_{causef}$ is the expected energy not supplied index associated with the cause of failure, which corresponds to failure record f, $ECOST_{causef}$ is the expected interruption cost index associated with the cause of failure, which corresponds to failure record f, j is the element in which the failure occurred (j can be any of these values: A, PL, PR, PT or PS), $EENS_j$ is the expected energy not supplied index associated with element j, $EENS_{jf}$ is the expected energy not supplied index associated with element j, which corresponds to failure record f, $ECOST_j$ is the expected interruption cost index associated with element j, $ECOST_{jf}$ is the expected interruption cost index associated with element j, which corresponds to failure record f, $\lambda_{circuit}$ is the average failure rate of the distribution circuit under study, $U_{circuit}$ is the annual outage duration of the distribution circuit under study, and $\lambda_{neighborhood}$ is the average failure rate in the given neighborhood.

3. First case study

A case study was performed for RELIABILITY-INDEXES-CALCULATION.xlsm. The circuit diagram of the first case study is as follows:

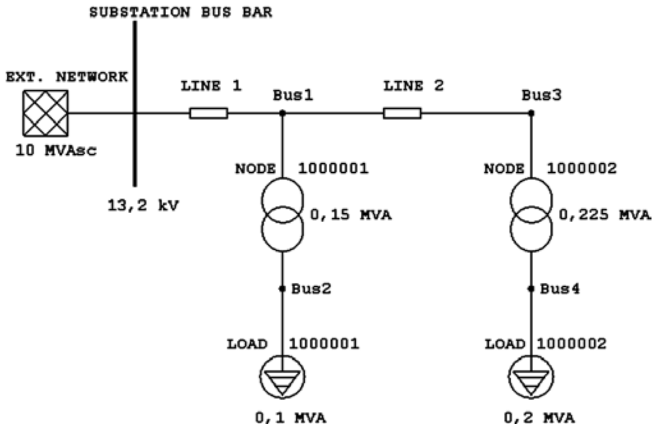

Figure 1. Diagram of the circuit for the first case study, solved by ETAP software and RELIABILITY-INDEXES-CALCULATION.xlsm.
Source: The authors.

SAIFI	16.0000 f / customer.yr
SAIDI	11.6750 hr / customer.yr
CAIDI	0.730 hr / customer interruption
ASAI	0.9987 pu
ASUI	0.00133 pu
EENS	3.310 MW hr / yr
ECOST	1,269,000.00 $ / yr
AENS	1.6550 MW hr / customer.yr
IEAR	383.384 $ / kW hr

Figure 2. Results obtained by ETAP software.
Source: The authors.

Table 1.
Data of RELIABILITY-INPUT-DATA.xls file.

Node with associated load	λA (failures / year)	λPL (failures / year)	λPR (failures / year)	λPT (failures / year)	λPS (failures / year)
1000001	1.50	5.50	3.00	0.00	7.00
1000002	1.50	5.50	3.00	5.00	0.00
Node with associated load	**UA (hours / year)**	**UPL (hours / year)**	**UPR (hours / year)**	**UPT (hours / year)**	**UPS (hours / year)**
1000001	0.30	4.95	2.70	0.00	5.65
1000002	0.30	3.85	2.10	3.50	0.00
MONEYi (currency)	**ENERGYi (kWh)**	**IEARi (currency / kWh)**	**Ni (users)**	**Pi (kW)**	
21870000.00	64800.0	337.50	1	100.0	
53833846.1538462	129600.0	415.384615384615	1	200.0	

Source: The authors.

Table 2.
RELIABILITY-INDEXES-CALCULATION.xlsm execution results.

SAIFI	16.00	customer failures / (cust. year)
SAIDI	11.675	customer hours / (cust. year)
CAIDI	0.7296875	customer hours / cust. failure
ASAI	99.8667237442922	%
ASUI	0.133276255707756	%
EENS	3.31	MWh / year
ECOST	1269000.00	currency / year
AENS	1655.00	kWh / (customer year)
IEAR	383.383685800604	currency / kWh

Source: The authors.

Reliability input data are shown in Table 1. Results obtained and generated by using the RELIABILITY-INDEXES-CALCULATION.xlsm application are shown in Table 2. Results obtained by using of ETAP software are shown in Fig. 2. As can be seen, the results obtained with ETAP software are the same as those obtained through the RELIABILITY-INDEXES-CALCULATION.xlsm application. According to these results, on average a customer suffers: 16 electrical faults per year, 11.675 hours without electricity per year, 0.73 hours without electricity per failure, and 1655 kWh without consuming per year. For the distribution circuit under study: The electrical service is provided for a total of 99.87% of the time, the electrical service is not provided for a total of 0.133% of the time, 3.31 MWh per year is the expected amount of energy that is not supplied, $1269000.00 per year is the expected interruption cost of this energy, and $383.384 per kWh is the interrupted energy assessment rate.

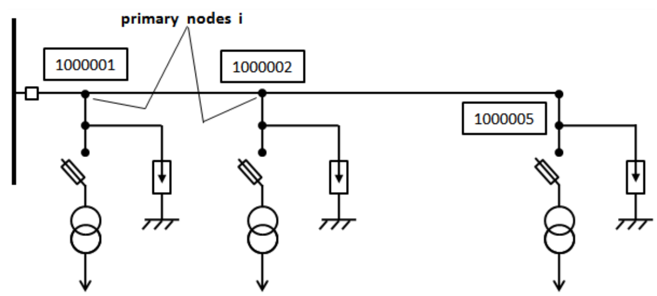

Figure 3. Unifilar diagram of the circuit for the econd case study, solved by RELIABILITY-INPUT-DATA-AND-STATISTICS.xlsm.
Source: The authors.

4. Second case study

A case study was performed for the RELIABILITY-INPUT-DATA-AND-STATISTICS.xlsm application. The unifilar diagram of the circuit for the second case study is shown as follows:

Causes of failure are shown in Table 3, and these causes appear in causes.xls file. The content of the BASIC-DATA worksheet belonging to the circuit.xls file is shown in Table 4. The content of the FINANCIAL-INFORMATION worksheet belonging to the circuit.xls file is shown in Table 5. The content of the NODE-INFORMATION worksheet belonging to the circuit.xls file is shown in Table 6. As can be seen, the circuit under study corresponds to UNIVERSE ZONE. The application does not take into account other circuits that are different to the one which appears in the BASIC-DATA worksheet belonging to the circuit.xls file. Thus, PLANET ZONE circuit was not taken into account by RELIABILITY-INPUT-DATA-AND-STATISTICS.xlsm.

Table 3.
Causes of failure used for the second case study.

CAUSE ID	CAUSE DESCRIPTION	Can you clear this cause of failure by means of a recloser? (TRUE / FALSE)
1000	CORRECTIVE MAINTENANCE - MAINTENANCE AND OPERATION OF AERIAL LINE	FALSE
1100	PRIMARY EQUIPMENT FAILURE	FALSE
1500	SUBSTATION EQUIPMENT FAILURE	FALSE
2000	FAILURE AT CUSTOMER INSTALLATIONS	FALSE
1700	OBJECTS OVER THE LINE - TREES OR BRANCHES – VEGETATION	TRUE
900	OBJECTS OVER THE LINE – BIRDS	TRUE
500	LIGHTNING – METEOROLOGY	FALSE

Source: The authors.

Table 4.
Content of the BASIC-DATA worksheet belonging to the circuit.xls file.

CIRCUIT	UNIVERSE ZONE	
CIRCUIT CODE	10 300	
PERIOD UNDER ANALYSIS	2.0	Years
START DATE	03/01/2013	dd/mm/yy
FINAL DATE	31/12/2014	dd/mm/yy

Source: The authors.

Table 5.
Content of the FINANCIAL-INFORMATION worksheet belonging to the circuit.xls file.

NODE	CIRCUIT	MONEYi (currency)	ENERGYi (kWh)
1000001	UNIVERSE ZONE	8810000.00	20000.0
1000002	UNIVERSE ZONE	12322500.00	30000.0
1000005	UNIVERSE ZONE	4308000.00	10000.0
1000003	PLANET ZONE	6615000.00	15000.0
1000004	PLANET ZONE	10350000.00	25000.0

Source: The authors.

Table 6.
Content of the NODE-INFORMATION worksheet belonging to the circuit.xls file.

NODE	NEIGHBORHOOD	Ni (users)	Average monthly energy consumption in the last year $ENERGY_{AVERAGE-i}$ (kWh)
1000003	MELROSE PLACE	75	20160.0
1000004	ROOSEVELT AVENUE	125	30240.0
1000001	FOREST HILLS	100	10080.0
1000002	HIGH AVENUE	150	15120.0
1000005	LINCOLN SQUARE	50	25200.0

Source: The authors.

Table 7.
Content of columns A, B, C and D from the FAILURES worksheet belonging to the circuit.xls file.

OPENING EVENT	CLOSING EVENT	TYPE OF FAILURE	OPENING DATE
140000	140001	Network	31/12/2012 10:33
150000	150001	Network	03/01/2013 9:15
151000	151001	Substation	15/02/2013 14:38
151000	151001	Substation	15/02/2013 14:38
151000	151001	Substation	15/02/2013 14:38
151000	151001	Substation	15/02/2013 14:38
151000	151001	Substation	15/02/2013 14:38
162000	162001	Network	25/04/2013 21:09
162000	162001	Network	25/04/2013 21:09
162000	162001	Network	25/04/2013 21:09
173000	173001	Network	10/11/2013 9:39
203000	203001	Network	01/01/2014 10:16
215000	215001	Network	03/01/2014 16:20
325000	325001	Network	09/03/2014 3:40
455000	455001	Network	22/06/2014 11:16
567000	567001	Network	31/12/2014 23:59
567000	567001	Network	31/12/2014 23:59
655000	655001	Network	01/01/2015 11:16

Source: The authors.

Table 8.
Content of columns E, F, G and H from the FAILURES worksheet belonging to the circuit.xls file.

DURATION (MINUTES)	CIRCUIT CODE	NODE	CAUSE CODE
40.0	10 300	1000001	1000
30.0	10 301	1000015	1000
0.5	10 300	1000001	1500
0.5	10 300	1000002	1500
0.5	10 300	1000005	1500
0.5	10 300	1000003	1500
0.5	10 300	1000004	1500
90.0	10 300	1000003	1700
90.0	10 300	1000004	1700
90.0	10 300	1000005	1700
120.0	10 300	1000002	1100
270.0	10 300	1000005	2000
20.0	10 301	1000003	1000
45.0	10 300	1000001	1000
60.0	10 300	1000005	2000
270.0	10 300	1000002	500
270.0	10 300	1000005	500
70.0	10 300	1000002	2000

Source: The authors.

The content of the FAILURES worksheet belonging to the circuit.xls file is shown in Tables 7, 8 and 9. Executing the RELIABILITY-INPUT-DATA-AND-STATISTICS.xlsm application completes the content of the RELIABILITY-INPUT-DATA.xls file, as can be seen in Table 10. As such, the RELIABILITY-INDEXES-CALCULATION.xlsm application can process this last file in order to calculate the selected reliability indexes.

RELIABILITY-INPUT-DATA-AND-STATISTICS.xlsm allows all the data contained in the worksheets belonging to the RELIABILITY-STATISTICS.xls file to be completed. Consequently, the results of the worksheet CAUSES-GENERAL-REPORT are shown in Table 11. The results of the FAILURES-PER-NEIGHBORHOOD worksheet can be seen in Table 12. The results from the EENS-ECOST-PER-ELEMENT worksheet are shown in Table 13.

Table 9.
Content of columns I and J from the FAILURES worksheet belonging to the circuit.xls file.

CAUSE DESCRIPTION	OBSERVATIONS
CORRECTIVE MAINTENANCE - MAINTENANCE AND OPERATION OF AERIAL LINE	Failure of the secondary network
CORRECTIVE MAINTENANCE - MAINTENANCE AND OPERATION OF AERIAL LINE	The secondary network was repaired
SUBSTATION EQUIPMENT FAILURE	T1's breaker on the 13.2 kV side
SUBSTATION EQUIPMENT FAILURE	T1's breaker on the 13.2 kV side
SUBSTATION EQUIPMENT FAILURE	T1's breaker on the 13.2 kV side
SUBSTATION EQUIPMENT FAILURE	T1's breaker on the 13.2 kV side
SUBSTATION EQUIPMENT FAILURE	T1's breaker on the 13.2 kV side
OBJECTS OVER THE LINE - TREES OR BRANCHES – VEGETATION	Branches were removed from the primary network
OBJECTS OVER THE LINE - TREES OR BRANCHES – VEGETATION	Branches were removed from the primary network
OBJECTS OVER THE LINE - TREES OR BRANCHES – VEGETATION	Branches were removed from the primary network
PRIMARY EQUIPMENT FAILURE	Burned out transformer C6461/112.5 was removed and Siemens C23025/112.5 was installed on the 1000002 node
FAILURE AT CUSTOMER INSTALLATIONS	A transformer in poor condition was changed
CORRECTIVE MAINTENANCE - MAINTENANCE AND OPERATION OF AERIAL LINE	Failure of the secondary network
CORRECTIVE MAINTENANCE - MAINTENANCE AND OPERATION OF AERIAL LINE	The secondary network was repaired
FAILURE AT CUSTOMER INSTALLATIONS	Damaged circuit breaker was changed
LIGHTNING - METEOROLOGY	A gale appeared, a broken primary pole was isolated
LIGHTNING - METEOROLOGY	A gale appeared, a broken primary pole was isolated
FAILURE AT CUSTOMER INSTALLATIONS	Damaged circuit breaker was changed

Source: The authors.

Table 10.
Data from the RELIABILITY-INPUT-DATA.xls file are completed using RELIABILITY-INPUT-DATA-AND-STATISTICS.xlsm.

Node with associated load	λ_A (failures / year)	λ_{PL} (failures / year)	λ_{PR} (failures / year)	λ_{PT} (failures / year)	λ_{PS} (failures / year)
1000001	0.5	0	0	0	0.5
1000002	0.5	0.5	0	0.5	0
1000005	0.5	0.5	0.5	1	0

Node with associated load	U_A (hours / year)	U_{PL} (hours / year)	U_{PR} (hours / year)	U_{PT} (hours / year)	U_{PS} (hours / year)
1000001	0.004167	0	0	0	0.375
1000002	0.004167	2.25	0	1	0
1000005	0.004167	2.25	0.75	2.75	0

$MONEY_i$ (currency)	$ENERGY_i$ (kWh)	$IEAR_i$ (currency / kWh)	N_i (users)	P_i (kW)
8810000.00	20000.0	440.50	100	14.0
12322500.00	30000.0	410.75	150	21.0
4308000.00	10000.0	430.80	50	35.0

Source: The authors.

Table 11.
Data contained in Columns A, C, D, E, F, G, H, I and J are from the CAUSES-GENERAL-REPORT worksheet, which is part of the RELIABILITY-STATISTICS.xls file.

CAUSE ID	Number of valid failures records (failures)	Total sum of valid failures duration (minutes)	Λcause (failures / year)	Ucause (hours / year)
1000	1	45.00	0.50	0.375
1100	1	120.00	0.50	1.00
1500	3	1.50	1.50	0.0125
2000	2	330.00	1.00	2.75
1700	1	90.00	0.50	0.75
900	0	0.00	0.00	0.00
500	2	540.00	1.00	4.50

CAUSE ID	Sum of not supplied expected energies to the circuit due to valid failures (MWh)	EENScause (MWh / year)	Expected interruption cost (currency)	ECOSTcause (currency / year)
1000	0.0105	0.00525	4625.25	2312.63
1100	0.042	0.021	17251.50	8625.75
1500	0.000583333	0.000291667	248.9229167	124.4614583
2000	0.1925	0.09625	82929.00	41464.50
1700	0.0525	0.02625	22617.00	11308.50
900	0.00	0.00	0.00	0.00
500	0.252	0.126	106666.875	53333.4375

Source: The authors.

Table 12.
Data from the FAILURES-PER-NEIGHBORHOOD worksheet, which was taken from the RELIABILITY-STATISTICS.xls file.

CAUSE ID	CAUSE DESCRIPTION	FOREST HILLS	HIGH AVENUE	LINCOLN SQUARE
1000	CORRECTIVE MAINTENANCE - MAINTENANCE AND OPERATION OF AERIAL LINE	0.50	0.00	0.00
1100	PRIMARY EQUIPMENT FAILURE	0.00	0.50	0.00
1500	SUBSTATION EQUIPMENT FAILURE	0.50	0.50	0.50
2000	FAILURE AT CUSTOMER INSTALLATIONS	0.00	0.00	1.00
1700	OBJECTS OVER THE LINE - TREES OR BRANCHES – VEGETATION	0.00	0.00	0.50
900	OBJECTS OVER THE LINE – BIRDS	0.00	0.00	0.00
500	LIGHTNING – METEOROLOGY	0.00	0.50	0.50

Source: The authors.

RELIABILITY-INPUT-DATA-AND-STATISTICS.xlsm allows for the content of the INVALID-FAILURES worksheet to be completed, as can be seen in Table 15. This application also completes the content of the GENERAL-INFORMATION worksheet, as can be seen in Table 14.

Table 13.
Contents of the EENS-ECOST-PER-ELEMENT worksheet, which was taken from the RELIABILITY-STATISTICS.xls file.

ELEMENT j	RELIABILITY INDEX FOR ELEMENT j	CALCULATED VALUE	UNITS
A	$EENS_A$	0.000291667	MWh / year
PL	$EENS_{PL}$	0.126	MWh / year
PR	$EENS_{PR}$	0.02625	MWh / year
PT	$EENS_{PT}$	0.11725	MWh / year
PS	$EENS_{PS}$	0.00525	MWh / year
A	$ECOST_A$	124.4614583	currency / year
PL	$ECOST_{PL}$	53333.4375	currency / year
PR	$ECOST_{PR}$	11308.50	currency / year
PT	$ECOST_{PT}$	50090.25	currency / year
PS	$ECOST_{PS}$	2312.625	currency / year

Source: The authors.

Table 14.
Contents of the GENERAL-INFORMATION worksheet, which was taken from the RELIABILITY-STATISTICS.xls file.

Distribution circuit	UNIVERSE ZONE	
Period under analysis	2.0	years
Start date	03/01/2013	dd/mm/yy
Final date	31/12/2014	dd/mm/yy
Number of nodes with associated load	3	nodes
Total number of analyzed failure records	16	failures
Failure records number of the circuit under analysis	14	failures
Number of valid failure records of the circuit under analysis	10	failures

Source: The authors.

Table 15.
Contents of the INVALID-FAILURES worksheet, which was taken from the RELIABILITY-STATISTICS.xls file.

OPENING EVENT	CLOSING EVENT	TYPE OF FAILURE	OPENING DATE
151000	151001	Substation	15/02/2013 14:38
151000	151001	Substation	15/02/2013 14:38
162000	162001	Network	25/04/2013 21:09
162000	162001	Network	25/04/2013 21:09
DURATION (MINUTES)	**CIRCUIT CODE**	**NODE**	**CAUSE CODE**
0.5	10 300	1000003	1500
0.5	10 300	1000004	1500
90.0	10 300	1000003	1700
90.0	10 300	1000004	1700
CAUSE DESCRIPTION		**OBSERVATIONS**	
SUBSTATION EQUIPMENT FAILURE		T1’s breaker damage on the 13.2 kV side	
SUBSTATION EQUIPMENT FAILURE		T1’s breaker damage on the 13.2 kV side	
OBJECTS OVER THE LINE - TREES OR BRANCHES – VEGETATION		Branches were removed from the primary network	
OBJECTS OVER THE LINE - TREES OR BRANCHES – VEGETATION		Branches were removed from the primary network	

Source: The authors.

According to Table 10: Node 1000001 only has active failures and passive failures in the secondary network system. For this node, failures in the secondary network system have the longest outage duration. In fact, active outage durations are the shortest for the three nodes under study. Node 1000002 has failures everywhere except in the secondary network system and on the primary line, for which faults can be cleared by means of a recloser. For this node, failures on the primary line, the faults of which cannot be cleared by means of a recloser, have the longest outage duration. Node 1000005 has failures everywhere except on the secondary network system. This node has the longest outage duration and the largest failure rate, given by passive failures, for primary electrical equipment composed of a transformer, fuses and a surge arrester. According to Table 11, the largest number of failure records corresponds to cause ID 1500 (SUBSTATION EQUIPMENT FAILURE), the longest duration of the total sum of valid failures corresponds to cause ID 500 (LIGHTNING - METEOROLOGY), the largest amount of expected energy not supplied that is associated with the cause of failure is equal to 0.126 MWh / year for cause ID 500 (LIGHTNING - METEOROLOGY). This cause ID also has the largest expected interruption cost. According to Table 12, the FOREST HILLS neighborhood has the smallest number of failures per year, and the LINCOLN SQUARE neighborhood has the largest amount of failures per year.

According to Table 13, the largest amount of expected energy not supplied associated with element j is equal to 0.126 MWh per year, for which the element j corresponds to passive failures take place on the primary line, and the faults cannot be cleared by means of a recloser. The largest expected interruption cost associated with element j is equal to $53333.4375 per year, and the element j is the same as was previously mentioned. According to Table 14, the number of nodes with an associated load is equal to 3, the number of analyzed failure records is equal to 16, the number of failure records for the circuit under analysis is equal to 14, and the number of valid failure records for the UNIVERSE ZONE circuit is equal to 10.

From a practical point of view, Table 15 indicates the reconfiguration influence of the distribution circuit. In this case, nodes 1000003 and 1000004 are not listed inside the UNIVERSE ZONE circuit, as can be seen in Table 5.

5. Conclusions

For the First case study, the SAIFI index is equal to 16.0 customer failures / (customer year). Ideally, the SAIFI index should be equal to zero; however, this is, practically, impossible because in a real distribution system there are a lot of contingencies during the course of a year. Thus, it is necessary to compare the SAIFI index for the same distribution circuit for different years. In this manner, is possible to measure the electrical service quality for a certain distribution circuit. This method is valid for the rest of the known reliability indexes, with the exception of the ASAI (Average Service Availability Index). Ideally, this index should be equal to 1 (100%). For the First case study, the ASAI index is equal to 0.9987, which is a good value. The CAIDI index measures the speed that the electrical service is repaired. For the First case study, the CAIDI index is equal to 0.73 customer hours / (customer failure). This value should be smaller.

For the Second case study, according to Table 10, the largest sum of failure rate associated with element j is equal to 1.5 failures / year, which corresponds to: λ_A (active failure rate) and λ_{PT} (passive failure rate for primary electrical equipment composed of a transformer, fuses and a surge arrester). Based on this, the electric utility must work on frequency reduction for these types of failures. The largest sum of outage duration associated with element j is equal to 4.5 hours / year, which corresponds to: U_{PL} (passive outage duration on the primary line, the failures of which cannot be cleared by means of a recloser). As such, the electric utility must work on increasing the reparation speed for this type of failures.

According to Table 11, the electric utility must work on reducing the frequency of cause ID 1500 (SUBSTATION EQUIPMENT FAILURE). In the same way, the electric utility must work on increasing the reparation speed for cause ID 500 (LIGHTNING - METEOROLOGY). According to Table 12, the electric utility must work on improving the quality of service for the LINCOLN SQUARE neighborhood. According to Table 13, the electric utility must work on increasing the reparation speed for faults associated with passive failures on the primary line, the faults of which cannot be cleared using a recloser.

For the EMCALI EICE ESP company, and for all Colombian electric utilities, is impossible calculate the CCDF for element j according to eq. (5). As such, it was impossible calculate the $ECOST_i$ index. By using the new methodology presented in this document it is now possible to calculate the $ECOST_i$ index as it is possible to calculate the Composite Customer Damage Function at load point i, $CCDF_i$, according to eq. (7)-(8). The INVALID-FAILURES worksheet is fundamental to be able to find out the number of invalid failure records that belong to the circuit under study but present primary nodes that do not appear on the FINANCIAL-INFORMATION worksheet or the NODE-INFORMATION worksheet. Invalid failure records are very common in the Colombian electricity market due to the reconfiguration of distribution circuits. The reconfiguration of distribution circuits is widely used in the EMCALI EICE ESP company's Strategic Energy Business Unit. Thus, the new methodology presented in this document is extremely useful for this enterprise as well as for any Colombian electric utility.

References

[1] Chowdhury, A.A. and Koval, D.O., Value-based distribution system reliability planning. IEEE Transactions on Industry Applications, 34, pp. 23-29, 1998. DOI: 10.1109/TIA.2004.834075

[2] Chowdhury, A.A., Distribution system risk assessment based on historical reliability performance. Electro Information Technology, 2005 IEEE International Conference on, pp. 1-7, 2005. DOI: 10.1109/EIT.2005.1626967

[3] Mercados Energéticos Consultores., Prestación de servicios para determinar los niveles de calidad exigibles en las redes del SIN, Colombia, CREG, 2014, 236 P.

[4] Zhu, T.X., A new methodology of analytical formula deduction and sensitivity analysis of EENS in bulk power system reliability assessment. IEEE Power Systems Conference and Exposition, pp. 825-831, 2006. DOI: 10.1109/PSCE.2006.296422

[5] Liu, N., Zhang, L. and Han, X., Unit commitment considering expected customer interruption cost. Probabilistic Methods Applied to Power Systems (PMAPS), 2010 IEEE 11th International Conference on, pp. 120-125, 2010. DOI: 10.1109/PMAPS.2010.5528985

[6] Lim, J., Choi, J. and Cha, J., Web based online real-time outage cost assessment information system of power system-II. Innovative Smart Grid Technologies (ISGT), 2013 IEEE PES, pp. 1-6, 2013. DOI: 10.1109/ISGT.2013.6497870

[7] IEEE. IEEE Guide for electric power distribution reliability indices, IEEE Std 1366-2012. New York: IEEE Standards Association, 2012. DOI: 10.1109/IEEESTD.2012.6209381

[8] Operation Technology INC. Distribution system reliability analysis [online], [consulted, 10 of november of 2015]. Avalaible at: https://www.youtube.com/watch?v=S70BIoEXLlk&feature=youtu.be

[9] Comisión de Regulación de Energía y Gas. Resolución 119 de 2008. Bogotá: CREG, 2008.

[10] Zapata, C.J., Granada M. y Reyes, G.A., Reposición de activos de sistemas de distribución de energía eléctrica basada en el aspecto de confiabilidad. Mundo Eléctrico, 90, pp. 56-65, 2013.

[11] Comisión de Regulación de Energía y Gas. Resolución 179 de 2014. Bogotá: CREG, 2014.

[12] Comisión de Regulación de Energía y Gas. Información y formatos para la presentación del plan de inversions, Resolución CREG 179 de 2014. Bogotá: CREG, 2015.

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