Optimal placement of switching and protection equipments, and the impact of the installation of fault indicators on reliability indices

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***Summary*—In this paper, it is presented algorithms to determine the optimal locations of switching and protection equipments in a distribution network in order to improve its reliability. It also presents an algorithm to evaluate the impact of the installation of fault indicators on the reliability indices. For the modeling and programming of the used algorithms, the software for simulation of electrical power systems DIgSILENT PowerFactory was used. The article also describes the results of applying these algorithms in seven electrical distribution systems.**

***Keywords*—Reliability, switching, protection, fault indicators, distribution network.**

I. Introduction

The basic function of a power system is to provide electric power to users with acceptable degree of continuity and quality [1].

Analysis of failure statistics shows that due to radial configuration of feeders and to the high rate of failures of equipment and sections of these feeders, distribution systems contribute in major proportion to the unavailability of electricity supply to users.

There are two main ways to improve the reliability of distribution systems. The first is to reduce the interruption frequency, and the second is to reduce the outage duration once the failure occurs. With the installation of switching and protection equipments and fault indicators, it is possible to improve the reliability indices.

The switching equipments improve reliability indices because they isolate the area where the faulted element is located, allowing restore the power supply to areas without faults, meanwhile, the faulted element is repaired.

A protective equipment conveniently placed on a feeder, allow to interrupt, if a fault occurs in its protection zone, the power supply in such zone, allowing continuity of service for the upstream zone from such equipment, and allowing that a lower numbers of users be affected by interruptions.

The fault indicators reduce the time to locate a fault on overhead lines feeders, thus reducing the duration of an interruption. The location time is reduced even more if fault indicators are equipped with communication devices [3].

In this paper is presented results of the application of mentioned algorithms, in seven overhead distribution systems.

The results show that placing properly switching and protection equipments and installing conveniently fault indicators, it is possible to improve significantly reliability indices.

II. TECHNIQUE OF STATE ENUMERATION

The state enumeration technique (analytic) consist in determine the states in which the system under study could be operating.

The analytical technique represents to the system by using simplified mathematical models and evaluates the reliability indices of such models using mathematical solutions. When the network is taken into consideration, it is essential to model the system rules and operating policies, even by means of analytical techniques.

The general procedure involves three steps:

- Systematic selection of states and their evaluation.
- Classification of contingencies according to predetermined criterions of faults.
- Compilation of appropriate predetermined reliability indices.

The state enumeration technique has been incorporated in the reliability module of PowerFactory DIgSILENT software, which is used to determine reliability indices [6].

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III. RELIABILITY PARAMETERS

For the evaluation of the system reliability, some data for each element that compose a distribution network is required, they are failure rate and repair time.

Failure rate: the number of failures of a component per year caused by a permanent outage. These failures could be caused by misoperation, lightning, animals, short circuits, trees, overloading, leak of insulation, etc.

The outage rate is obtained by dividing the total number of failures of a given equipment by the total of components and divided by the number of years.

The following expression is presented:

$$\lambda = Fa / (N \times T) \quad (1/\text{year}) \qquad (1)$$

Where:
Fa: number of failures observed for a certain type of element,
N: number of components exposed to failure.
T: period of observation in years.

Repair time: represents the action of replacement or reparation of component which cause the outage of service, it also represents the period from turning off the circuit to reenergizing it.

The repair time is the average time of a failure, expressed in hours, and it depends of the associated protection and of the type of work to be done to restore power (switching actions, repairs, cleaning, etc.).

The average duration of outage is obtained by dividing the total outage duration caused by the failed equipment by the total number of events involved in the equipment.

IV. RELIABILITY INDICES

The reliability indices used for electrical networks pretend to quantify the quality of the service that has the network at any point of consumption. Figure 1 shows the parameters to be taken into account for the calculation of reliability and the results to be obtained.

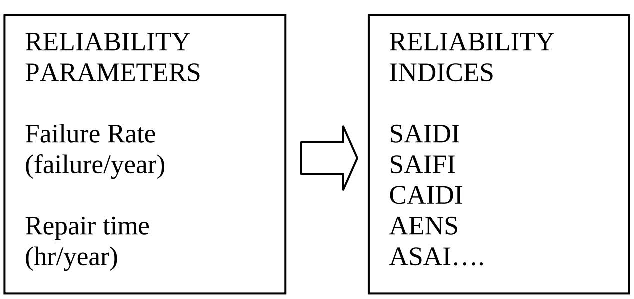


Figure 1. Parameters and reliability indices

The reliability indices can be calculated for the entire system as well as for important load points (priority zone). The main indices used for the entire system are divided into three groups and are within the following classification:

- Frequency indices.
- Duration indices.
- Indices for momentary interruptions.

The Standard IEEE Std 1366-2003 [5] specified reliability indices that are grouped under the classification indicated above, highlighting as the most important, are detailed below:

A. *SAIFI (system average interruption frequency index)*

The system average interruption frequency index indicates how often the average customer experiences a sustained interruption over a predefined period of time.

$$\text{SAIFI} = \frac{\sum \text{Total Number of Customers Interrupted}}{\sum \text{Total Number of Customers Served}} \qquad (2)$$

B. *SAIDI (system average interruption duration index)*

This index indicates the total duration of interruption for the average customer during a predefined period of time. It is commonly measured in customer minutes or customer hours of interruption.

$$\text{SAIDI} = \frac{\sum \text{Customer Interruption Durations}}{\sum \text{Total Number of Customers Served}} \qquad (3)$$

C. *CAIDI (customer average interruption duration index)*

CAIDI represents the average time required to restore service.

$$\text{CAIDI} = \frac{\sum \text{Customer Interruption Duration}}{\sum \text{Total Number of Customers Interrupted}} \qquad (4)$$

V. MODELING AND TECHNIQUE OF EVALUATION

The modeling of the electrical distribution system is made such that load flow and reliability simulations could be performed. This includes to consider: the load model, the system of generation and distribution system, and the failure model for feeder sections (main and laterals).

In this paper, it is assumed that the protective devices are properly adjusted and coordinated.

A. *Switching and protection equipment*

In the case of the optimal placement of switching and protection equipment, it is used an iterative algorithm, which evaluates, from a group of possible places, the best placement for a group of switching equipments available for installation, achieving to improve the SAIDI value. Similarly, an iterative algorithm is used for the case of the optimum placement of protective equipment, but the difference is that in this case both SAIDI and SAIFI values vary. Figure 2 describes the algorithm of evaluation.

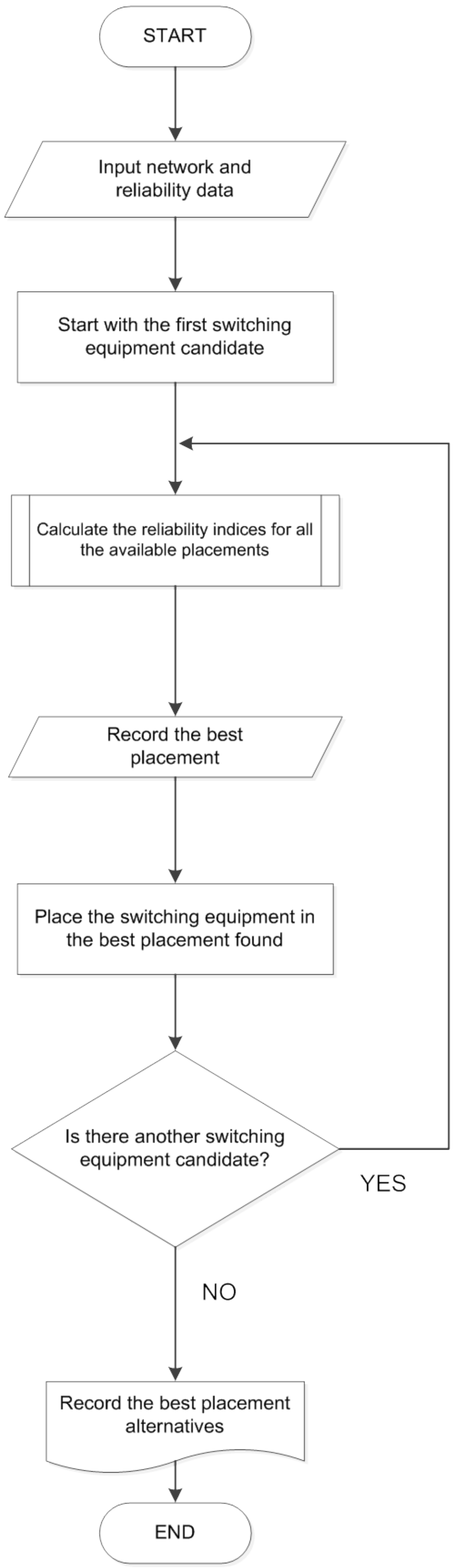


Figure 2. Algorithm for placement of switching and protective equipment

B. *Fault indicators*

The fault indicators (FI) permit to reduce the fault location time on overhead line feeders, reducing the duration time of an interruption, and improving the SAIDI indicator. If the fault indicators are equipped with devices for sending signals to a control center, the fault can be located quickly using the GIS system.

In an electrical distribution system, usually after the occurrence of a fault in a feeder, it is identified and isolated the faulted section of the network, then the service is restored to un-faulted feeder sections, and faulted section is repaired. This process is shown in Figure 3.

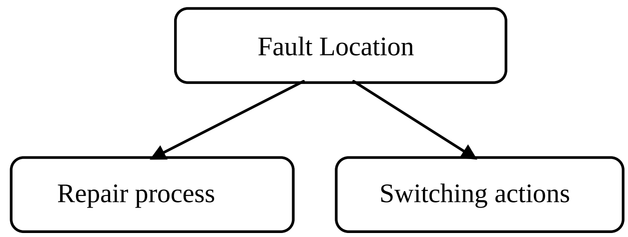
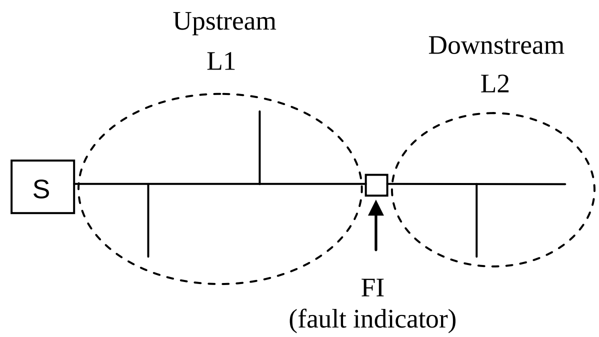


Figure 3. Action after a failure occurrence

The installation of fault indicators can reduce the fault location time and consequently increase the system reliability. For example a typical feeder with a fault indicator is shown in Figure 4.



L1: sum of the lengths of main and lateral sections upstream from the fault indicator
L2: sum of the lengths of main and lateral sections downstream from the fault indicator

Figure 4. Typical distribution system with fault indicator

Assuming average fault location time of this feeder, without fault indicator, is T_0 hours. With the installation of a fault indicator, the fault location time for upstream part of the feeder is:

$$T_1 = T_0 * L1/(L1 + L2) \quad (5)$$

And for downstream part is:

$$T_2 = T_0 * L2/(L1 + L2) \quad (6)$$

In general, with installation of n fault indicators on a distribution feeder, that feeder is divided to n+1 parts and fault location time for ith part (T_i) can be calculated as follow:

$$T_i = T_0 \left(\frac{L_i}{\sum_{j=1}^{n+1} L_j} \right) \qquad (7)$$

i = 1, 2, 3, …, n+1

Where:
L_i: Length of part ith
T_0: Average fault location time of feeder without FI.

Figure 5 describes the evaluation procedure.

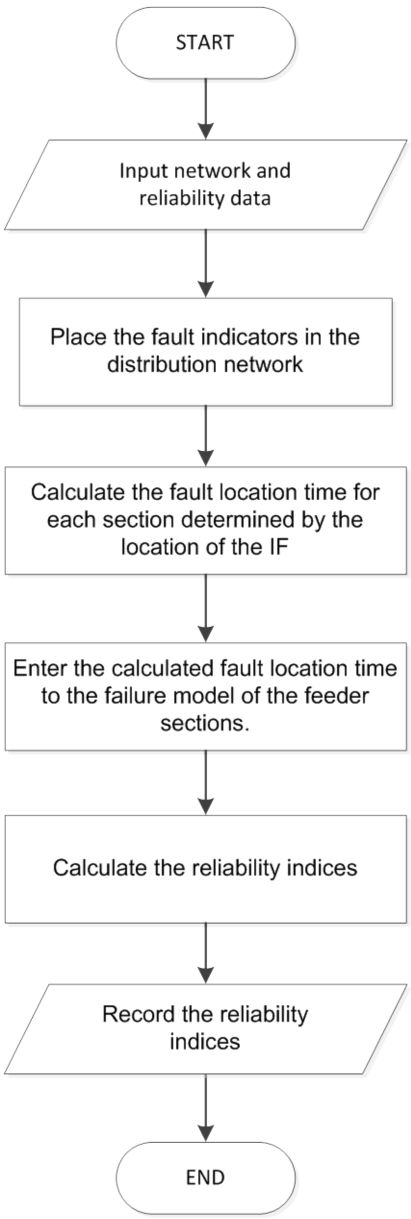


Figure 5. Algorithm for evaluating the impact of the FI

VI. IMPLEMENTATION

For the implementation of the used models and algorithms, DPL (DIgSILENT Programming Language) scripts have been developed in the software DIgSILENT PowerFactory.

For modeling, required data of the electrical system are:

- Load Model
- Generation System
- Distribution network
- Failure Model
- Number of switching equipments to be installed
- Number of protection equipment to be installed
- Possible locations of switching and protection equipment.
- Location of fault indicators.

The data is entered into the database of the PowerFactory DIgSILENT software.

VII. APPLICATION CASES

In the Peruvian electricity system, there are 200 electrical distribution systems, classified in five typical sectors, plus a special typical sector. From all these systems, 142 are considered critical because they exceed tolerances, from them 74 are considered moderately critical and 41 are considered highly critical.

From the 200 electrical systems, the following electrical distribution systems have been taken as test systems:

- Huaytará – Chocorvos's electrical system.
- San Francisco's electrical System
- Pozuzo's electrical system
- Chalhuamayo – Satipo's electrical System
- Tarma – Chanchamayo's electrical System
- Ticapampa's electrical System
- Guadalupe Rural's electrical System

These electrical systems were chosen because they are considered critical due to they have high values of SAIFI and SAIDI exceeding the tolerances of the Peruvian regulations [7], [8], [9].

The following tables show the SAIFI and SAIDI values of the distribution systems in 2012, and the differences regarding to the tolerances.

TABLE I
SAIFI Values

Electrical System	SAIFI – Dist.	Expected Performance (EP)	Difference (EP-SAIFI)	Difference (EP-SAIFI) [%]
Huaytará – Chocorvos	80.9	16.0	64.9	405.9%
San Francisco	42.8	7.0	35.8	511.6%
Pozuzo	127.1	16.0	111.1	694.3%
Chalhuamayo - Satipo	59.5	12.0	47.5	396.0%
Tarma - Chanchamayo	17.3	7.0	10.3	147.7%
Ticapampa	22.1	12.0	10.1	84.4%
Guadalupe Rural	56.2	7.0	49.2	703.3%

TABLE II
SAIDI Values

Electrical System	SAIDI – Dist.	Expected Perform ance (EP)	Difference (EP-SAIDI)	Difference (EP-SAIDI) [%]
Huaytará – Chocorvos	467.0	40.0	427.0	1067.6%
San Francisco	149.3	12.0	137.3	1143.8%
Pozuzo	413.0	40.0	373.0	932.4%
Chalhuamayo - Satipo	67.6	24.0	43.6	181.5%
Tarma - Chanchamayo	23.1	12.0	11.1	92.4%
Ticapampa	89.1	24.0	65.1	271.2%
Guadalupe Rural	96.6	12.0	84.6	705.2%

The number of users and reliability data are entered directly into the database of the PowerFactory DIgSILENT software.

Reliability data has been determined based on the reports of interruptions reported by the distribution company, and it is shown in the following table:

TABLE III
Reliability Data

Section	Failure Rate (failure/year/km)	Repair Time (hours)	Sectionalizing time (horas)
Huaytará – Chocorvos			
Main	0.22	4.10	0.5
Lateral	0.55	8.30	0.5
San Francisco			
Main	0.27	2.01	0.5
Lateral	0.68	4.08	0.5
Pozuzo			
Main	1.05	2.36	0.5
Lateral	2.63	4.78	0.5
Chalhuamayo - Satipo			
Main	2.06	0.69	0.5
Lateral	5.17	1.39	0.5
Tarma - Chanchamayo			
Main	1.31	0.72	0.5
Lateral	3.29	1.45	0.5
Ticapampa			
Main	0.30	2.26	0.5
Lateral	0.76	4.57	0.5
Guadalupe Rural			
Main	3.36	1.05	0.5
Lateral	8.42	2.13	0.5

Simulations have been performed for the following cases:

A. Case A: placement of the switching equipments

For the case of the installation of switching equipments, a determined number of switching equipments have been considered to be installed taking into account the network size, with several alternative of placement. The program determines the locations where the switching equipments should be installed to achieve a greater reduction of SAIDI value.

B. Case B: placement of protection equipments

In the case of the installation of protective equipments, a determined number of protection equipments have been considered to be installed taking into account the network size, with several alternative of placement (same amount as those considered in case A). The program determines the locations where should be installed these protective equipment in order to achieve a greater reduction in SAIDI, and SAIFI.

For each case, after defined the placement of the switching and protection equipments, it is evaluated the effect of the installation of fault indicators on the reliability indices. For this, it is used a determined number of fault indicators to be installed taking into account the network size, conveniently placed for quick localization.

The figures 6 to 8 show partial diagrams of some analyzed systems.

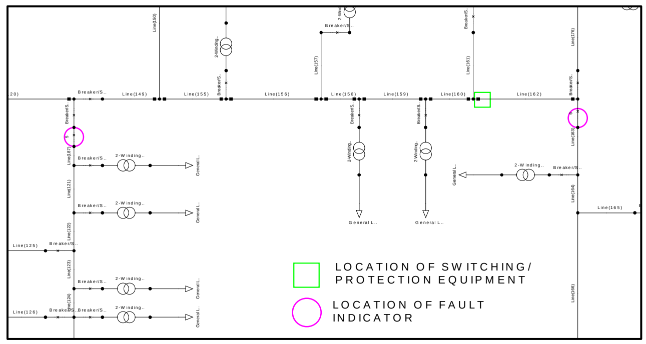


Figure 6. Huaytará– Chocorvos's electric system

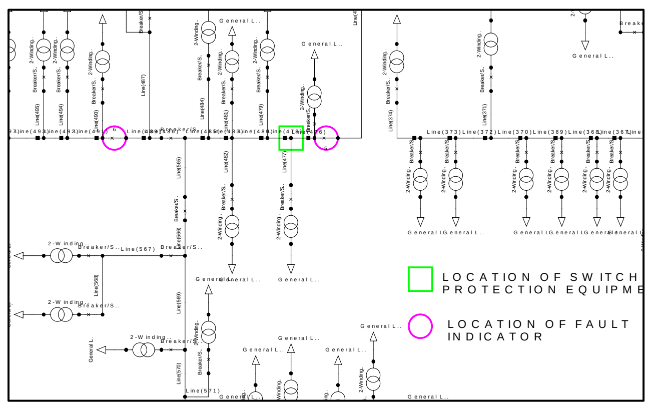


Figure 7. San Francisco's electric system

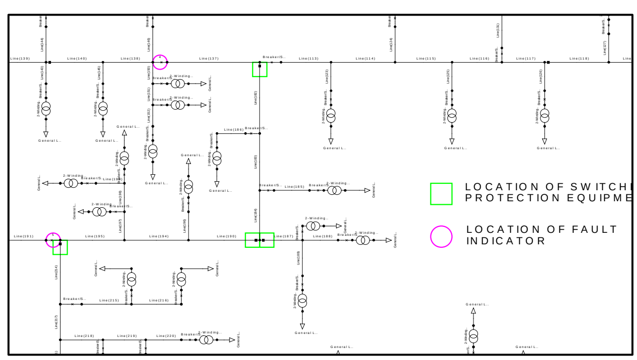


Figure 8. Ticapampa's electric system

The results of the simulations are shown in the following tables:

TABLE IV
Results of Case A

Indices	Initial Case	With switching equipments placed by the program		With switching equipments and fault indicators	
Huaytará – Chocorvos					
SAIFI	35.86	35.86	0.00%	35.86	0.00%
SAIDI	188.25	153.03	18.71%	108.61	42.31%
San Francisco					
SAIFI	42.90	42.90	0.00%	42.90	0.00%
SAIDI	149.80	136.10	9.15%	96.30	35.71%
Eléctrico Pozuzo					
SAIFI	127.60	127.60	0.00%	127.60	0.00%
SAIDI	412.10	409.30	0.68%	295.10	28.39%
Chalhuamayo - Satipo					
SAIFI	59.40	59.40	0.00%	59.40	0.00%
SAIDI	67.98	64.71	4.81%	44.62	34.37%
Tarma - Chanchamayo					
SAIFI	17.72	17.72	0.00%	17.72	0.00%
SAIDI	23.23	23.02	0.91%	17.04	26.65%
Ticampampa					
SAIFI	22.00	22.00	0.00%	22.00	0.00%
SAIDI	89.08	69.10	22.43%	48.58	45.46%
Guadalupe Rural					
SAIFI	56.23	56.23	0.00%	56.23	0.00%
SAIDI	96.77	88.13	8.93%	68.32	29.40%

The table IV shows that with the switching equipments conveniently placed by the program, SAIDI indices are reduced between 0.68% and 22.43% compared to the initial case for the analyzed electrical systems. With the addition of fault indicators, SAIDI index is reduced between 26.65% and 45.46% compared to the initial case.

TABLE V
Results of Case B

Indices	Initial Case	With protection equipments placed by the program		With protection equipments and fault indicators	
Huaytará – Chocorvos					
SAIFI	35.86	27.16	24.26%	27.16	24.26%
SAIDI	188.25	148.68	21.02%	104.27	44.61%
San Francisco					
SAIFI	42.90	38.20	10.96%	38.20	10.96%
SAIDI	149.80	133.70	10.75%	94.00	37.25%
Pozuzo					
SAIFI	127.60	126.60	0.78%	126.60	0.78%
SAIDI	412.10	408.80	0.80%	294.60	28.51%
Chalhuamayo - Satipo					
SAIFI	59.40	53.92	9.23%	53.92	9.23%
SAIDI	67.98	61.97	8.85%	41.88	38.40%
Tarma - Chanchamayo					
SAIFI	17.72	17.49	1.28%	17.49	1.28%
SAIDI	23.23	22.90	1.41%	16.93	27.14%
Ticampampa					
SAIFI	22.00	16.93	23.04%	16.93	23.04%
SAIDI	89.08	66.56	25.28%	46.05	48.31%
Guadalupe Rural					
SAIFI	56.23	50.55	10.12%	50.55	10.12%
SAIDI	96.77	85.29	11.86%	65.47	32.34%

The table V shows that with the protective equipments conveniently placed by the program, SAIFI indices are reduced between 0.78% and 24.26% compared to the initial case for the analyzed electrical systems, also SAIDI indices are reduced between 0.8% and 25.28% compared to the initial case. With the addition of fault indicators, SAIDI indices are reduced between 27.14% and 48.31% compared to the initial case, for the same electrical system.

VIII. CONCLUSION

The results show that placing properly the switching and protection equipments, and installing conveniently fault indicators, it is possible to improve significantly the reliability indices.

It is proposed to evaluate 41 electric systems considered highly critical for the Peruvian electricity system, to determine in which of these systems their reliability indices can be significantly improved with the optimal installation of switching and protection equipment, and the installation of fault indicators.

Improving the reliability indices using the optimal placement of switching and protection equipment, and installation of fault indicators, it should be complemented by others strategies such as the maintenance and strengthening of distribution lines, right of way management, proper location lightning arresters, among others, in order to reduce failure rates and repair time, and at the same time reducing the values of SAIDI and SAIFI.

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X. BIOGRAPHIES

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