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SIPOWER'95 Cancún, México 1995.

EVALUATION AND IMPROVEMENT OF RELIABILITY INDEXES IN ELECTRIC DISTRIBUTION SYSTEMS

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Abstract A methodology for the evaluation of reliability indexes in medium voltage radial distribution power systems is presented. A general reliability index is obtained as well as loss frequency and duration indexes for customers and individual installations. Also, a linear optimization methodology is developed to identify networks elements where investments allow to increase availability level for any customer in the system. A computer program is designed, tested and used to evaluate several test electrical distribution systems.

Key Words Distribution systems, power quality, reliability, availability, optimization.

1. INTRODUCTION

The evaluation of reliability indexes in medium voltage electric distribution systems has been presented by various authors in the last decade (Billinton *et al*, 1975; Allan *et al* 1976; Allan *et al*, 1979). Distribution companies search for the highest availability in their systems, measured through indexes based on frequency and duration. The most common indexes are SAIDI, SAIFI, CAIDI, CAIFI and ASAI (Billinton *et al*, 1984).

Reliability evaluation techniques for distributions systems have evolved from those developed for transmission systems (Gaver *et al*, 1964; Billinton *et al*, 1968). Markov processes used in those systems were replaced by network methods for reliability predictive evaluation and have become the standard, given their easy technical and computational handling. Network methods involve the determination of minimal cuts sets, series/parallel reduction and other techniques. Monte Carlo simulation methods have also been reported, with results that agree with other techniques.

2. SCOPE OF RELIABILITY EVALUATION

Distribution utilities are facing increasing requirements for higher levels of power quality, where service continuity is the essential parameter. Therefore the need is there not only to evaluate reliability, but also to determine actions that will allow to increase service availability. Evidently, this depends on the regulatory requirements for the utilities and the level of consumer satisfaction.

The paper first contributes with a method to evaluate reliability indexes in distribution networks. It is based on the study of failure modes and effect analysis. It is applicable to any radial distribution system. In the study of failure modes, the following are considered:

-failure modes: active, passive, momentary outages

-philosophy of network operation: sectionalizer management, overload accepted levels, etc.

-protection philosophy: set points, coordination schemes, protection elements.

The method predicts reliability, based on the knowledge of frequency individual indexes (fault rate) and fault duration. Fault rate and duration are classified according to the type of fault considered. The data may be obtained from historical records, manufacturers data, company experience with similar equipment or from average performance of equipment in operation. For any consumer, the reliability analysis of the different fault modes provides a first order reliability model. All elements that affect service availability are connected in series, without relation to network topology. The results provide a State Matrix that is also useful for sensitivity analysis. There are as many matrices as types of faults considered.

The first order reliability model, for the calculation of failure rate and duration, may be solved with equations derived for series reliability systems (Billinton *et al*, 1984).

When reliability indexes are poor (not satisfying regulation requirements or consumer demands), there is clearly the need to improve the performance of the networks and the level of power quality. The paper proposes a methodology that will help the decision process in the improvement of network reliability. The interest is one of determining which investments will report higher benefits. An optimization problem is formulated, where the objective function is the investment cost, and constraints correspond to the increase of service availability. Increase of service is expressed in hours per year. Other constrains are failure rate limits and repair times limits. Variables obtained from the optimization are changes of failure rates and repair times.

A linear optimization algorithm is formulated, with costs assigned to failure rates and repair time variations. Solutions considered in the optimization processes are: equipment upgrading, equipment change, increase of maintenance personnel, improvement of maintenance policies, automatization, computerization, etc., each having different costs and impacts.

3. METHODOLOGY

3.1 General formulation

The basic information required for the reliability evaluation includes network topology and reliability parameters assigned to individual elements (failure rate and failure duration). The methodology allows to include the failure of protection elements, but these failures are not modeled at this stage.

The network model represents sectionalizer elements (including protection elements) and feeder segments. Each feeder segment has its own failure rate and average duration, only accounting its failure events.

The general reliability evaluation is based on the determination of a *State Matrix*, that takes into account the operative state when a feeder segment experiments a event. These events are: active faults (involving protection operations), and passive faults (outages without protection operation). The events considered result in different State Matrixes, allowing to evaluate each impact.

Operative states considered include the following:

–***Normal*** (N): the state of feeder segment i is normal when the faulted segment j or the protections associated to it do not affect the continuity of supply.

–***Restaurative*** (R): the state of feeder segment i is restaurative, when before the element j is repaired, it is possible to recover service, isolating the faulted element.

–***Transferable*** (T): the state of feeder segment i is transferable when, being affected by the failure of element j, it is possible to connect it to an alternative source.

–***Non-restaurative*** (I): the state of feeder segment i is non-restaurative when being affected by the failure of element j, it is not possible to get electrical supply until element j is finally repaired.

–***Non-restaurative and waiting*** (E): the state of feeder segment j, in failure, is designed as non restaurative and waiting, when before its repair, there exists a transference action to another source.

The failure duration is composed of several intervals, identified as:

TC: corresponds to the time interval between failure occurrence and the utility acknowledgment.
TP: corresponds to the time interval between the utility acknowledgment and the selection of the appropriate elements and materials for repair.
TL: corresponds to the time spent in the identification of the exact fault position.
TT: time wasted in transference actions
TR: repair duration.
TV: time wasted in transference actions for normal operation scheme.

3.2 State Matrix formulation

The method to formulate the *State Matrix* is explained, considering only active failures. A similar approach would follow with other failure types (passive failures, momentary outages, etc.).

A failure in each feeder segment, one at a time, is simulated. The feeder segment operative states are identified as described above, analyzing the result of that failure. A matrix is formed, where column i indicates the state of the feeder segment i when a failure is considered in element j (corresponding to row j). Obviously, the states depend on the protection policy and management of sectionalizer elements. In this paper, we assume that if there is an alternative source, all feeder segments affected could connect to it.

Different states have different durations, as indicated in Table 1. The time intervals depend on the electrical capabilities, automation, personnel, etc.

Table 1 Individual failure rates and failure durations

State	Fail. Rate	Fail. Duration
Normal	0	0
Restaurative	λ	TC+TP+TL
Transferable	2λ	TC+TP+TL+TT+TV
Non-restaurative	λ	TC+TP+TL+TR
Non-rest waiting	λ	TC+TP+TL+TT+TR

Parameter λ is the fault rate considering events in a particular feeder segment, as indicated above.

3.3 Evaluation of indexes

The reliability model obtained from the State Matrix permits to evaluate the frequency and duration contributions easily, given it corresponds to a series configuration.

$$\lambda_i = \sum_j \lambda_i^j \tag{1}$$

$$U_i^j = \lambda_i^j \cdot r_i^j \tag{2}$$

$$U_i = \sum_j U_i^j \tag{3}$$

$$r_i = \frac{U_i}{\lambda_i} = \frac{\sum_j \lambda_i^j r_i^j}{\sum_j \lambda_i^j} \tag{4}$$

where:

λ_i^j : contribution of feeder segment j to the fault rate of the feeder segment i [faults/year], according to Table 1,

λ_i : feeder segment i fault rate [faults/year],

U_i^j : contribution of feeder segment j to the unavailability of the feeder segment i, [hours/year],

U_i : annual unavailability of the feeder segment i, [hours],

r_i^j : interruption time of the feeder segment i, because of fault in the feeder segment j, [hours], refer to Table 1,

r_i : equivalent interruption time of the feeder segment i, [hours].

4. IMPROVEMENTS BY OPTIMIZATION

The unavailability U for a feeder segment, depends on the contributions of different elements in the network. Taking the partial derivative with respect to each contribution and linearizing, we get:

$$\frac{\partial U_i}{\partial \lambda_j} = r_j \tag{5}$$

$$\frac{\partial U_i}{\partial r_j} = \lambda_j \tag{6}$$

$$\Delta U_i = \sum_j r_j \cdot \Delta\lambda_j + \sum_j \lambda_j \cdot \Delta r_j \tag{7}$$

A change in the electrical supply availability is identical to a change in the probability of succesful electrical service, in some sense called *reliability*. Moreover, it has an economic impact for the utilities, by considering higher income and better satisfaction of regulatory constrains. Therefore, we may formulate the following optimization problem, aimed at obtaining a higher availability level in some load point assigned to a feeder segment, while looking for a minimal investment:

$$\min\left[\sum c_{\lambda j} \cdot \Delta\lambda_j + \sum c_{rj} \cdot \Delta r_j\right] \tag{8}$$

subject to:

$$\Delta U_i = \sum_j r_j \cdot \Delta\lambda_j + \sum_j \lambda_j \cdot \Delta r_j \tag{9}$$

$$r_{\min.} < r_i < r_{\max.} \tag{10}$$

$$\lambda_{\min.} < \lambda_i < \lambda_{\max.} \tag{11}$$

The problem so formulated is identical to obtaining a higher supply probability.

The cost specification associated to λ and r variations in equation (8) allows to formulate a linear optimization problem or an integer optimization problem. The cost parameters take into account the investments required to generate a change in fault rate and time repair.

A simplified approach is possible. It consists in eliminating the possibility of failure rate variations, concentrating the efforts in obtaining lower time repairs. The time variations can be evaluated with a good precision.

5. PROPOSED ALGORITHM

The proposed reliability evaluation methodology and optimization process can be formulated into an algorithm in the following sequence:

a. Determine individual feeder segment reliability parameters and costs associated to investments considered.

b. Determine the State Matrix, according to the normal operating topology.

c. Evaluate, using equations (1) to (4) and the State Matrix, the fault rate, time repair and unavailability for each feeder segment.

d. If a higher level of availability in a particular feeder segment is desired, one must select the desired level change.

e. The optimization problem must be formulated through equations (8) to (11).

f. Solving the optimization problem, optimal changes are obtained, minimizing the investments.

g. Re-evaluate the reliability indexes.

6. APPLICATION SYSTEM

The reliability methodology evaluation developed and the optimization process is applied to a 15 kV urban feeder of a Chilean electric utility, as shown in Fig. 1.

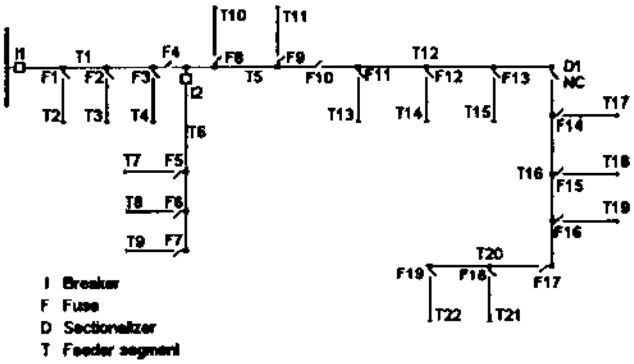

Fig. 1 15 kV urban feeder

Table 2 Reliability parameters

Feeder	λ	km	TC	TL	TP	TT	TR	TV	Users
T01	0.05	2	5	5	5	5	90	5	0
T02	0.08	5	5	5	5	5	90	5	100
T03	0.08	4	5	5	5	5	120	5	250
T04	0.02	10	5	5	5	5	60	5	120
T05	0.02	4	5	5	5	5	120	5	0
T06	0.02	5	5	5	5	5	90	5	0
T07	0.10	3	10	10	10	10	90	10	100
T08	0.04	2	10	10	10	10	90	10	150
T09	0.05	5	10	10	10	10	90	10	250
T10	0.05	10	10	10	10	10	90	10	80
T11	0.05	3	10	10	10	10	90	10	200
T12	0.05	5	10	10	10	10	120	10	0
T13	0.04	5	10	10	10	10	100	10	100
T14	0.04	2	10	10	10	10	100	10	250
T15	0.05	10	10	10	10	10	90	10	300
T16	0.04	4	10	10	10	10	90	10	0
T17	0.05	5	10	10	10	10	120	10	250
T18	0.04	55	5	5	5	5	100	5	200
T19	0.05	6	5	5	5	5	100	5	200
T20	0.05	4	5	5	5	5	90	5	0
T21	0.05	4	5	5	5	5	120	5	250
T22	0.10	55	10	10	10	10	120	10	300

The reliability parameters considered are listed in Table 2. λ is the individual fault rate, in [1/years]; km corresponds to the length of the segment feeder; TC, TL, TP, TT, TR and TV correspond to the time intervals explained in 3.1, expressed in [minutes]; users is the number of consumers connected to the feeder segments.

Table 3 provides the results obtained from the reliability evaluation.

Table 3 Reliability indexes

Feeder segmet	Fault rate 1/year	Time hours	Unavailability hours/year
T 1	0.10	1.75000	0.175
T 2	0.50	1.75000	0.875
T 3	0.42	2.13095	0.895
T 4	0.30	1.41667	0.425
T 5	0.18	1.97222	0.355
T 6	0.28	1.89286	0.530
T 7	0.58	1.94828	1.130
T 8	0.36	1.91667	0.690
T 9	0.53	1.94340	1.030
T 10	0.68	1.99265	1.355
T 11	0.33	1.98485	0.655
T 12	0.59	1.79661	1.060
T 13	0.79	1.89030	1.493
T 14	0.67	1.84080	1.233
T 15	1.09	1.88991	2.060
T 16	0.59	2.20339	1.300
T 17	0.84	2.29167	1.925
T 18	0.79	2.13080	1.683
T 19	0.89	2.10674	1.875
T 20	0.79	2.08861	1.650
T 21	0.99	2.12121	2.100
T 22	1.29	2.24806	2.900

Considering the number of consumers indicated in Table 2, the system indexes SAIDI and SAIFI are evaluated:

SAIDI = 1.528 [hours/year]
SAIFI = 0.745 [1/year]

Focusing on the goal of obtaining a higher level of availability in the feeder segment T22, changing from 2.9 to 2.5 [hours/year], the optimization problem can be presented as:

$$\text{Min } [C_1 \Delta r_1 + C_5 \Delta r_5 + C_{12} \Delta r_{12} + C_{16} \Delta r_{16} + C_{20} \Delta r_{20} + C_{22} \Delta r_{22}]$$

subject to

$$0.4 = 0.1\Delta r_1 + 0.08\Delta r_5 + 0.25\Delta r_{12} + 0.16\Delta r_{16} + 0.20\Delta r_{20} + 0.50\Delta r_{22}$$

$$0 < \Delta r_1 < 0.50$$
$$0 < \Delta r_5 < 0.50$$
$$0 < \Delta r_{12} < 0.50$$
$$0 < \Delta r_{16} < 0.50$$
$$0 < \Delta r_{20} < 0.50$$
$$0 < \Delta r_{22} < 0.50$$

Table 4 Cost of reduction of repair time

Feeder segment	Cost
T1	2
T2	2
T12	1
T16	2
T20	3
T22	4

As a result of the optimization process and the unit costs, the following changes are obtained, expressed in [hours]:

$\Delta r_1 = 0$
$\Delta r_5 = 0$
$\Delta r_{12} = 0.50$
$\Delta r_{16} = 0.15625$
$\Delta r_{20} = 0$
$\Delta r_{22} = 0.50$

7. CONCLUSIONS

This paper has presented an investment analysis methodology and an approach to evaluate the impact in the reliability indexes for a radial distribution system. An application example is presented. It is a contribution to electric utilities increasingly interested in improving power quality. The method will help find the adequate investments to reach adequate levels of customer service.

The authors are working in further evaluation of the proposed algorithm, in aspects such as linearization, new investments and actual investments, larger networks and a precise definition of unitary costs, in the changing of fault rates and repair times.

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ACKNOWLEDGMENTS

The authors thank FONDECYT and DINV, Universidad de Antofagasta, for their financial support to this research.