The Application of the Logical Structural Matrix for Reliability Analysis in a Distribution System Planning Environment

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ABSTRACT

In this paper, it is presented the application of the Logical Structural Matrix (LSM) to evaluate performance of reliability indexes. . In order to present and evaluate the methodology, a study over the reliability indices is made, considering the allocation of protection and switching devices in different point of a simplified network. After that, the methodology is applied to a real distribution system, for which different planning scenarios are proposed. The reliability indices are then calculated for all scenarios. The results are discussed in order to validate the methodology proposed.

INTRODUCTION

Recently, due to changes in the market and due to the environment created by the advent of smart grids and distributed generation (DG), the distribution system planning has become an even more important matter to power utilities. This change occurs on both consumer and power utilities side of view, since an adequate planning aims to reduce costs while keeps the consumers satisfied [1]. These characteristics are enhancing the search for alternative solutions to the problem of distribution system planning.

Among these alternative solutions, it is possible to find applications of DG [2], location of sectionalizing switches [3], locations of compensating devices such as capacitor banks [4], different network structures such as radial or meshed [5], Smart Grid concepts and Electric Vehicles [2], [6].

The integration of new technologies to the distribution systems directly influences the traditional methodologies applied in distribution system planning studies, once they have to take into account the impact of these technologies in the analysis of planning scenarios.

It requires many studies in order to achieve a balance between the energy demand growth and technical and financial restrictions. It usually involves the optimization of many objectives such as cost of installation of new facilities, cost of maintenance and operation, reliability of network, power loss and node voltage deviation, for example.

On the matter of reliability analysis, a number of works approaching the optimization of network reliability in distribution planning environment has been reported on literature. However, most of them analyzes reliability by estimating only the Energy Non-Supplied (ENS) index [5], [7], [8]. On the other hand, SAIDI and SAIFI indexes are usually not considered in this kind of analysis.

It is important to mention that the reliability improvement of a distribution network can be done using sectionalizing switches and tie-lines [3]. While sectionalizing switches are placed in a network to isolate faults, tie-lines are used to provide supply to some feeder branches due to faults occurring in an upstream branch of the network. An effective allocation of these devices is really important for the utilities, since that procedure is closely related to the restoration time and consequently associated with reliability index [9].

Having these devices as alternative solutions for distribution planning and knowing that new components will be introduced into the electric power system such as telecom, sensors, smart meters, automated devices, power electronics and control systems, it is important to know how these new components will affect the system and its reliability. In addition to that, it is important to highlight that Brazilian regulation over reliability indexes financially penalized the utilities by the noncompliance with reliability standards.

Considering these premises, this paper presents a methodology to estimate reliability performance of System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI) and Energy Not Supplied (ENS) indices based on the Logical Structural Matrix (LSM), aiming to analyze different planning scenarios and the respective impact of them over the reliability performance of the distribution system.

ESTIMATING RELIABILITY INDEXES BY LSM

SAIDI, SAIFI and ENS are the major distribution system indexes related to network reliability. Regarding to the distribution system analysis, they correspond to the expected values of:

- System Average Interruption Duration Index:

$$SAIDI = \frac{\sum interrupted\ consumers\ x\ interruption\ duration}{total\ number\ of\ consumers\ served} \quad (h/year) \qquad (1)$$

- System Average Interruption Frequency Index:

$$SAIFI = \frac{total\ of\ consumers\ interruptions}{total\ number\ of\ consumers\ served}\ (/year) \quad (2)$$

- Energy Not Supplied Index:

$$SAIFI = \sum interrupted\ power\ x\ interruption\ duration\ (kWh/year) \quad (3)$$

These indexes are obtained from the LSM [9], [10] by considering the following inputs:
- Mean Time to Restore Supply (TR);
- Number of consumers attended by each distribution transformer (N);
- Annual failure rate (λ);
- Load (P) of each distribution transformer.

While each column of the matrix represents a branch of the distribution network protected by a specific protective or switching device, each row corresponds to a distribution transformer of the network. To each cell, it is set initial values of TR. In order to define these values, it is required to analyze how long it takes to power supply restoration for the corresponding consumers (matrix line), when they are faced with a failure in the distribution network assuming the protective and switching equipment installed on the network (matrix column).
In order to exemplify how LSM works, a simplified distribution network is presented in Fig 1, for which the LSM is set. In this case, it is assumed that the NO switch at node 3 is connected to another feeder that is capable of attend loads downstream of the NC switch.

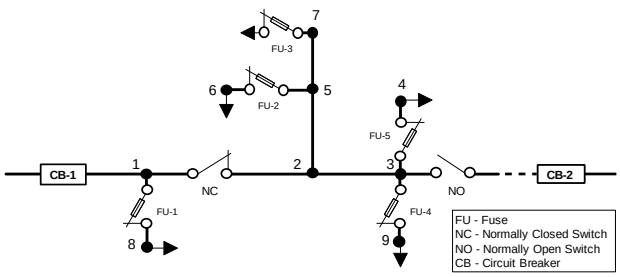

Fig. 1. Simplified distribution network.

Table 1 shows the LSM structured to the system of Fig. 1.

Table 1. LSM with mean times and failure rates.

Node	Protective and switching equipment						
	CB	NC switch	FU-1	FU-2	FU-3	FU-4	FU-5
1	$TR_1.\lambda_1$	$TI.\lambda_2$	0	0	0	0	0
2	$TT.\lambda_1$	$TR_2.\lambda_2$	0	0	0	0	0
3	$TT.\lambda_1$	$TR_2.\lambda_2$	0	0	0	0	0
4	$TT.\lambda_1$	$TR_2.\lambda_2$	0	0	0	0	$TR_7.\lambda_7$
5	$TT.\lambda_1$	$TR_2.\lambda_2$	0	0	0	0	0
6	$TT.\lambda_1$	$TR_2.\lambda_2$	0	$TR_4.\lambda_4$	0	0	0
7	$TT.\lambda_1$	$TR_2.\lambda_2$	0	0	$TR_5.\lambda_5$	0	0
8	$TR_1.\lambda_1$	$TI.\lambda_2$	$TR_3.\lambda_3$	0	0	0	0
9	$TT.\lambda_1$	$TR_2.\lambda_2$	0	0	0	$TR_6.\lambda_6$	0

In Table 1, TT represents the mean time to transfer; TI represents the mean time of isolation; and TR the mean time of restoration. As it is possible to notice, in case of an outage of the Circuit Breaker (CB), all consumers are affected, so for all of them the TR is considered, except those downstream the NC switch, for which is considered the time to transfer (TT) the loads to another feeder. Regarding the outage of fuses (FU), it only affects its downstream consumers, so the total time to restore power is computed. The upstream nodes are not affected by the fault, not suffering interruption, since the fuse is coordinated to blow before the circuit breaker trips (trip saving scheme). Then, the values of the matrix are multiplied by the failure rate of the respective equipment, as shown in Table 1. The result in each cell of the matrix is then used to calculate the expected reliability indexes for the network.
To calculate the expected value of SAIDI, SAIFI and ENS, the equations (4), (5) and (6) are applied, as follows:

$$SAIDI_e = \frac{\sum_{i=1}^{n}\left(\sum_{j=1}^{m} M_{i,j}\right).N_i}{N_c} \quad (4)$$

where $SAIDI_e$ is the expected value of system average interruption duration index (h/year); $M_{i,j}$ is the element in row i and column j of LSM; N_i is the number of consumers for the row i; N_c is total number of customers served.

$$SAIFI_e = \frac{\sum_{i=1}^{n}\left(\sum_{j=1}^{m} M_{i,j}^{*}\right).N_i}{N_c} \quad (5)$$

where $SAIFI_e$ is the expected value of system average interruption frequency index (failures/year); $M_{i,j}^{*}$ is the element in row i and column j of LSM.

$$ENS_e = \frac{\sum_{i=1}^{n}\left(\sum_{j=1}^{m} M_{i,j}^{*}\right).N_i}{N_c} \quad (6)$$

where ENS_e is the expected value of energy not supplied (kWh/year); Li = load, active power, associated to row i (kW).

RELIABILITY ANALYSIS IN A PLANNING ENVIRONMENT

A distribution planning study usually is ascertained by four distinct stages that commonly comprise different methodologies and analysis. The flow diagram in Fig. 2 shows the result of analysis.

Fig. 2. Stages for distribution planning studies.

Considering this schedule, the application of the LSM to analyze the reliability of planning scenarios is placed in the third stage: Technical and Financial Impact. Therefore, for this paper is assumed, at the stage of Diagnosis, the application of the classical backward/forward sweep method algorithm to calculate the power flow and Linear Regression as methodology to determine the load growth within the planning horizon, which is 5 years. At the Scenarios Formulation stage, in this case, three different solutions related to reliability improvement are proposed from the original network, considering both traditional solutions, such as new feeder routes, and alternative solutions, such as DG and allocation of remotely controlled switches.

In order to demonstrate the reliability analysis by the application of LSM, a simplified network is used. Figure 3 shows the system.

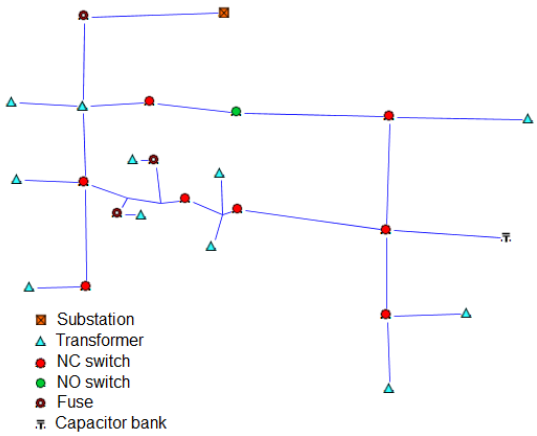

Fig. 3. Simplified network.

This network attends 271 consumers, with total load of 7.56MW. To calculate the reliability indexes, the mean times shown in Table 2 are considered.

Table 2. Mean Times of protective and switching devices.

Mean Time	Hour
TI	1h
TT	1h
TR	2h

In order to simplify the analysis it is assumed a failure rate $\lambda = 1$ failure/year to all protective and switching devices. It is also assumed that all the scenarios proposed are respecting the technical restrictions of voltage levels, loading and radial configuration of the network.

The results obtained from the LSM for this network configuration are shown in Table 3.

Table 3. Results from LSM

$SAIDI_e$	36h
$SAIFI_e$	18
ENS_e	289.58 kWh/year

Considering this results, three different scenarios are proposed, as follow.

Scenario 1

The first scenario proposed the addition of two new branches in the network plus the addition of a NO switch. With this configuration, it is expected to improve the flexibility of the network in case of isolation of a fault, reducing the reliability indexes. The Fig. 4 shows the new network configuration.

The same mean times and failure rates were considered in the LSM, for this scenario. The results obtained are shown in Table 4.

Table 4. Results from LSM – Scenario 1

$SAIDI_e$	24h
$SAIFI_e$	12
ENS_e	186.78 kWh/year

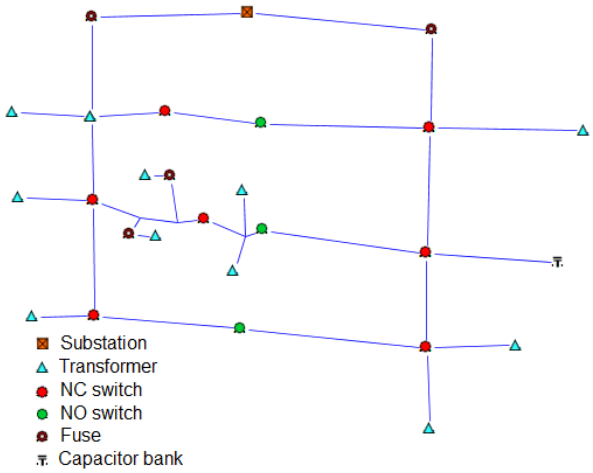

Fig. 4. Network configuration – Scenario 1.

As expected, the first scenario brought improvements, reducing all indices, since there are more possibilities to transfer loads in case of interruption, reducing the number of consumers affected.

Scenario 2

The second scenario presents the same configuration of Scenario 1 plus the addition of a DG of 1MW into the network. In this case, the isolate operation of the DG in case of an outage at the substation is not considered.

The network configuration of Scenario 2 is presented in Fig. 5.

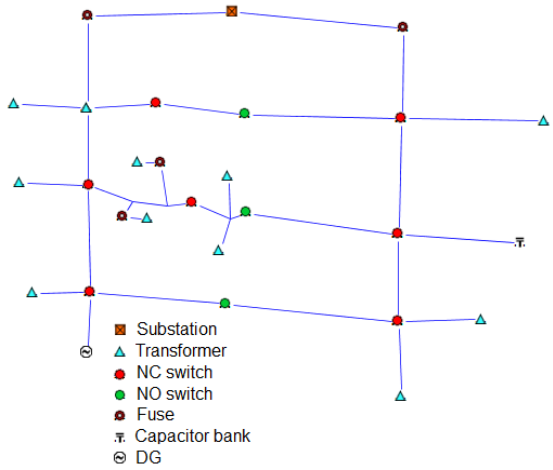

Fig. 5. Network configuration – Scenario 2.

Table 5 shows the results obtained for scenario 2.

Table 5. Results from LSM – Scenario 2

$SAIDI_e$	24h
$SAIFI_e$	12
ENS_e	161.26 kWh/year

As is possible to notice, the DG does not influence the performance of SAIDI and SAIFI indexes, if compared with Scenario 1 (without DG). However, it contributes to the improvement of the expected ENS, as shown in Table 5.

Scenario 3

The last scenario corresponds to the Scenario 2 plus the allocation of a remotely controlled (RC) switch in replacement of a normal switch. The Fig. 6 shows this configuration.

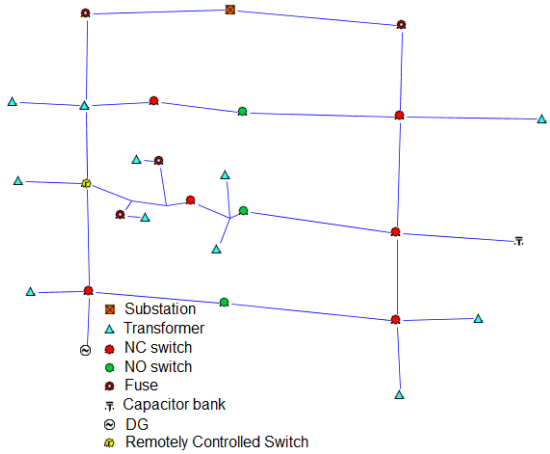

Fig. 6. Network configuration – Scenario 3.

Table 6 shows the results obtained for scenario 3.

Table 6. Results from LSM – Scenario 3

$SAIDI_e$	20.75h
$SAIFI_e$	10.38
ENS_e	158.10 kWh/year

The addition of a remotely controlled brings great improvements to the reliability indexes SAIDI, SAIFI and ENS. It is mostly related to the reduction of the time to restore the power supply. While a common switch requires a maintenance team to be operated, a RC switch is operated remotely from the operational center.

EXPERIMENTAL ANALYSIS

A Case Study have been performed considering real data from a Brazilian power utility, aiming at analysing the performance of the LSM when applied to a real system. The system considered is placed in a rural area and presents 6838 consumers attended by only one feeder.
The planning study was normally performed and after establishing a traditional scenario (reconductoring and new feeder routes) in order to attend to constrains of maximum loading and voltage levels, the reliability analysis was carried out by applying the LSM. From the results, the alternative planning scenario was proposed in addition to the traditional:

- Allocation of six remotely controlled switches;
- DG of 1MW.

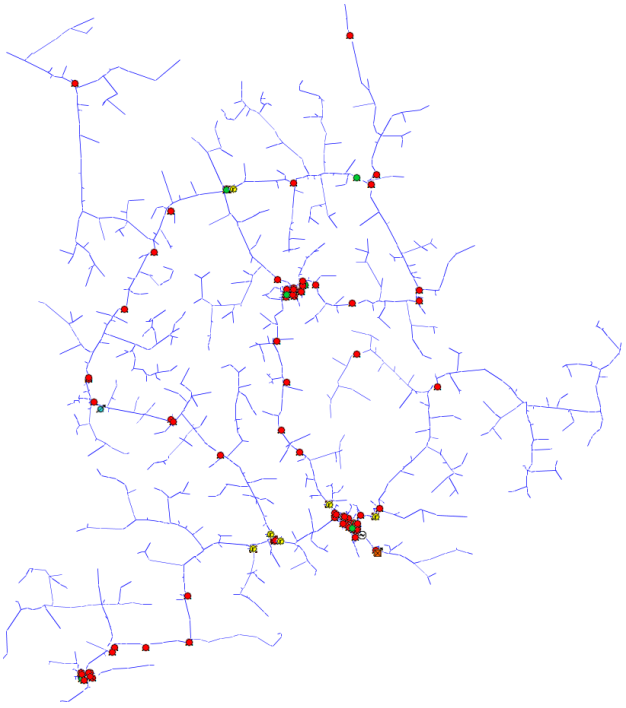

Fig. 7. Rural network considering the alternative planning scenario.

The results for both simulations are presented in Table 7

Table 7. Results from LSM – Scenario 3

Reliability indexes	Traditional	Alternative
$SAIDI_e$(h)	96.6	72.98
$SAIFI_e$	48.3	37.71
ENS_e (kWh)	334.84	209.12

As is possible to notice, the alternative solutions brought great improvements to the reliability indexes. While the allocation of remotely controlled switches improves the performance of SAIDI and SAIFI indexes, the allocation of the DG together with the RC switches reduce the ENS index. Despite it is not the focus of the paper, it is important to mention that the alternative solutions also contribute to the reduction of losses and the improvement of voltage levels.

CONCLUSIONS

In this paper was presented the application of the Logical Structural Matrix in a distribution system planning environment in order to calculate and evaluate the reliability performance. Alternative planning scenarios were proposed, considering DG and smart grid as solutions of the problem and their influence to the performance of SAIDI, SAIFI and ENS indexes was analyzed.
The LSM has shown itself as a good methodology to perform reliability analysis, indicating in a clear and objective way the direct variations of the reliability as different solutions are proposed. The further steps of this research is to integrate the LSM into a optimization algorithm, aiming at considering the minimization of SAIDI, SAIFI and ENS as objective function to determine the best planning scenarios for each network evaluated.

Acknowledgments

The authors would like to thank the technical and financial support of AES Sul Distribuidora Gaúcha de Energia SA (Programa P&D ANEEL), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul (FAPERGS) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

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