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Chapter 13

Coordination and Selectivity of Protection Devices with Reliability Assessment in Distribution Systems

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Abstract

This chapter provides an overview of the reliability of electricity distribution networks, and its evaluation that is linked with the protection system. In this way, the characteristics of network protection are presented, along with the peculiarities in coordination and device selectivity adjustments. For the assessment of the reliability, we have the methodology of logic-structural matrix (LSM) that integrates the constitution of the network with historical data of faults, so that with this, a model can be elaborated that can evaluate the impact of changes in the system directly on the reliability indicators.

Keywords: distribution network reliability, coordination and selectivity, protection system

1. Introduction

With the latest technologies and new concepts that have emerged, the electricity distribution system has become more flexible, but all this is reflected in general modifications of operation, planning, study, and analysis [1]. One of the great influencers in this environment is the smart grids, which changed the vision of a strongly static network and inserting versatility in the structure of the networks, using technologies, automation, and methodologies in a coupled manner [2, 3]. The uses of smart grid are wide ranging from load control, self-healing, voltage control, among others [4].

With the possibilities of this development, it inserts new complexities in the network and this can have both positive and negative impacts, due to which there are several factors or functionalities that must be reevaluated. Considering the main function of the power utilities being the transportation of energy to the final customer, we seek to use these new technologies and methods to increase the quality and safety of the service provided. In this way, one of the criteria most considered by the companies is the reliability of the network, both for strategic issues of network operation, and for the existence of financial penalties for not meeting targets [5–7].

The reliability of distribution networks is influenced by several factors like operation, maintenance, and planning [8], but as the reliability of the networks is directly linked to the interruptions in the power supply, one of the systems which has more impact is the protection [9]. Along with new automation, control, and communication technologies, some protection instruments have also advanced [10, 11], enabling reclosing, and different performance curves. In this way, the methodologies for adjusting the coordination and selectivity parameters of the devices must also consider a greater variety of factors, both those that can impact and those that can be impacted by this system.

Thus, it is proposed to evaluate the reliability of networks through their indicators considering the protection system. This will explore the main protection devices and how to obtain the main quality indicators, as well as verify the functionalities and main steps for coordination and selectivity of the device, in addition to modeling the network together with the factors that will directly impact the reliability of the distribution system.

2. Distribution network protection devices

The distribution systems of electric energy are composed of long networks, and are mostly aerial and made up of bare cables, due to the extension and exposure can cause failures or faults of various natures. Therefore, means for the protection of these systems become essential, for that, the protection devices are used. Moreover, the most used in distribution networks are the fuses and reclosers [12], which are discussed in the following subsections in detail.

2.1. Fuses

The protective devices that are most used in power distribution networks are the fuses. This is due to its low cost when compared to other protection devices and its satisfactory operation for one of the major problems of the distribution networks that refer to the overcurrent from short circuits by contact of the cables between each other, the vegetation or to the ground, and among others.

As a fuse-type protective device, it bases its operation on a metal link with specific characteristics of time versus current; when it reaches the maximum tolerable current, the heat melts the active element and releases the opening of circuit [13].

The construction of a fuse is divided into three elements: *Base*—Consists of an insulating material and serves as an interconnection between the moving parts and the support structure

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of the device. *Fuse tube*—Consists of an insulating material, serves as a support for the fuse link and is the moving part that promotes the opening between the terminals when the link fuses. *Fuse link*—Consisting of metal alloys with specific characteristics of melting temperature, it is the active element of protection of the equipment, having different types of links, with faster or slower curves depending on the application, the most common are types H and K. One example of fuse is represented in **Figure 1**.

2.2. Reclosers

Compared to fuses, reclosers have a relatively high cost, but these devices are more sophisticated and offer wider capabilities in protection, due to the measurement, automation, and the control possibilities. The reclosers have been increasingly used by electric power distributors; this happens due to the possibility of control and telecommunication of this device [14]. Through these characteristics, one can have a real-time control of the network allowing maneuvers for various purposes, thus contributing to the evolution of the smart grid.

The reclosers allow timed automatic reclosers; though this feature associated with fast curves, it is possible to minimize power interruptions caused by transient faults [15] such as contact of tree branches. In most devices, the timing system can be adjusted with fast or slow reclosing operations, or combinations thereof, depending on the need and philosophy of the company. This protection against transient faults also includes the networks protected by the fuses downstream of the reclosers. The construction of reclosers is more complex, and has a chamber for interrupt of electric arc, and there is current sensors and in some cases voltage sensors. One example of recloser is shown in **Figure 2**.

Regardless of the control and communication factors, the operating principle of the recloser is also related to the lack of current and its performance has a behavior described by current curves versus time. However, there are commercial models that are also made up of potential transformers; with this and the ability to communicate, these can protect the distribution system from other possible types of failures.

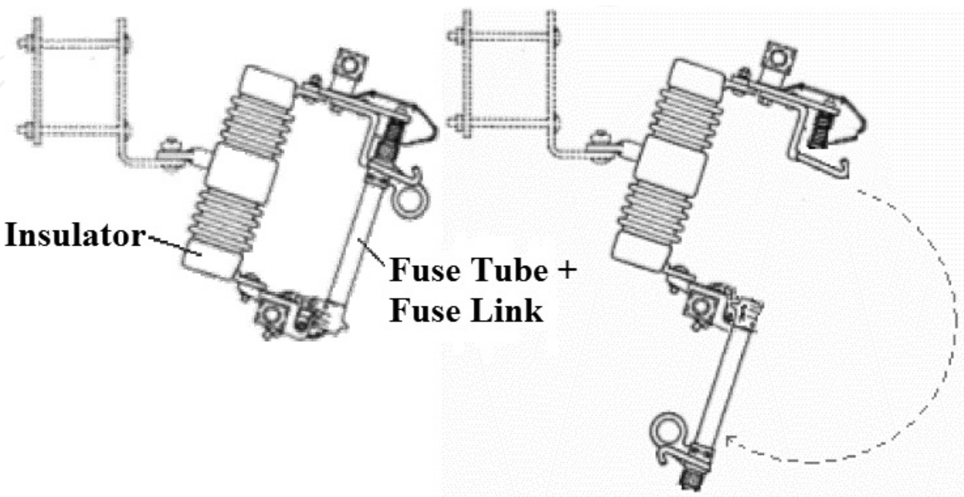

Figure 1. Medium voltage fuse.

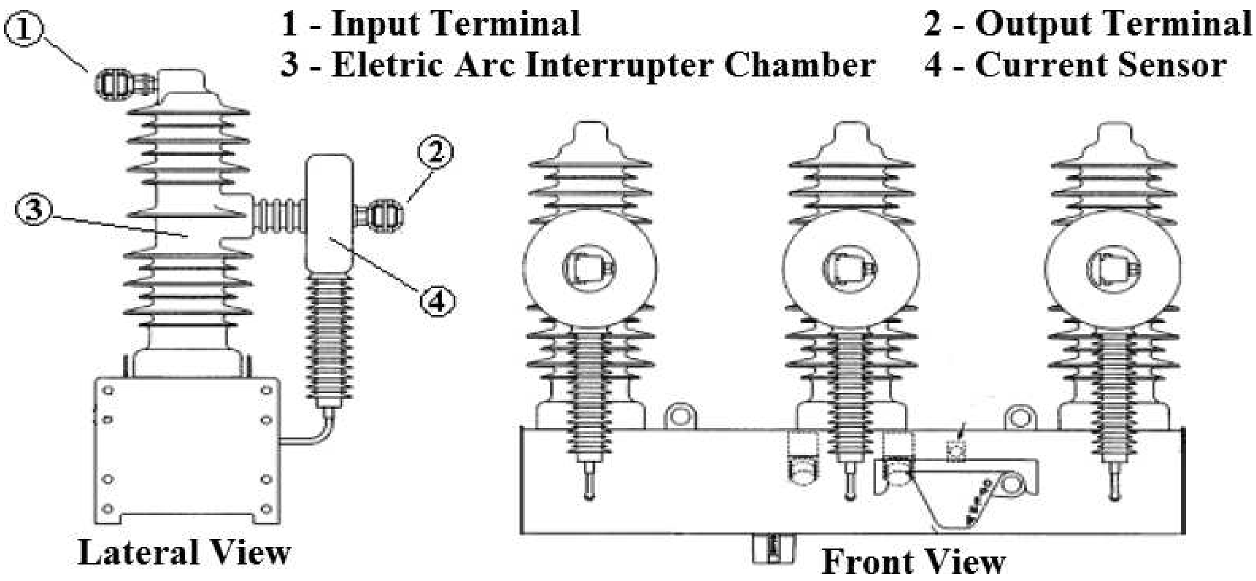

Figure 2. Recloser.

2.3. Coordination and selectivity

For proper protection of the electrical system, in addition to the use of appropriate devices, must be taken care with the sequence of operation of such equipment. This is necessary due to the fact that along the same network there are several devices and if this sequence of operation does not agree, there will be disconnection of undue loads, thus compromising the reliability of the system and may negatively influence the continuity indicators of the system from the power utility [16, 17].

The selectivity that refers to the sensitivity of the protection devices is evaluated first. This need arises since, that in addition to the interruption capacity of the devices, they need to be sensitized to operate in the minimum short circuit and at the same time allow the normal load current.

The criteria for selectivity of fuses can be summarized by Eq. (1) below:

$$K \cdot I_n \leq I_e \leq \frac{1}{4} \cdot I_{cc\min} \quad (1)$$

where

I_n–nominal load current of the circuit(A);

I_e–nominal current of the fuse link;

$I_{cc\min}$–minimum value of short-circuit current (A); and

K–demand growth rate.

For reclosers, since they have both phase and neutral settings, the settings can be expressed with the following Eqs. (2) and (3)

$$1.5 \cdot I_L \leq I_{pf} \leq \frac{I_{2\Phi F}}{2} \tag{2}$$

$$(0.1 \approx 0.3) \cdot I_c \leq I_p \leq \frac{I_{1\Phi m}}{2} \tag{3}$$

where

I_L–nominal load current of the circuit (A);

I_{pf}–pick-up current of phase, from recloser;

$I_{2\Phi F}$–biphasic current of short circuit;

I_p–pick-up current of neutral, from recloser; and

$I_{1\Phi m}$–single-phase current of short circuit.

In the other step, concerning coordination refers to the evaluation of the sequence of operation of the devices besides evaluating which devices downstream will be sensitized for upstream faults. This process seeks the best sequence of equipment performance, seeking to minimize the area affected by the fault or defect. In order to have the correct sequence, some criteria are used, depending on the type of equipment involved.

For coordination between fuses, we can cite three main criteria:

1. The nominal current of the protected link must always be higher than the rated current of the protective link.
2. Ideally, the protected fuse link (source side) must be coordinated with the protective link (load side) so as not to open first for the maximum short-circuit current at the point of installation of the protective link.
3. The coordination between two serial fuse links is guaranteed if the interruption time of the protective link is at most 75% of the minimum time of fusion of the protected link.

For coordination between fuses and reclosers, we can cite three main criteria that are explained as follows:

1. For all possible fault values within the circuit section protected by the fuse link, the minimum link fusion time must be greater than the recloser opening time multiplied by a factor *K* characteristic of the recloser, which varies depending on the number of fast operations adjusted and the reclosing time of the circuit.
2. For all possible fault values within the circuit section protected by the fuse link, the total time of the link interruption must be less than the minimum opening time of the recloser in its timed curve (slow curve), by adjusting the recloser for two or more timed operations.
3. In the case of not being able to coordinate between recloser and link for the whole range of short-circuit currents, it will be guaranteed at least the coordination for the condition of

single-phase faults involving contact impedance and maintained the selectivity to 80% maximum circuit.

3. Reliability in distribution networks

The term reliability has broad meaning and can refer to different applications in the same system. The authors of Ref. [18] define that the reliability of a system refers to the correct operation with full performance and no failure. Thus, the reliability is influenced by several factors, and may be manageable, such as planning, maintenance, and operation or unforeseen events such as storms or accidents.

For the main current regulations, the concept of reliability in the distribution of electricity is linked to interruptions in energy supply, which may be temporary (momentary) or sustained (permanent) [19]. This can be considered a subgroup of the perturbations that affect the quality of energy, as shown in **Figure 3**. The main disturbances that affect the quality can be frequency variations, noise, transient, harmonic distortions, temporary variation of voltage amplitude and properly the interruptions [20].

For the measurement and evaluation of the reliability of the distribution networks, the reliability indicators are used, these will be explained next. The evaluation of the power utilities is through these indicators, failure to comply with the stipulated values causes a penalty for the company and a discount to the final consumer. Thus in power systems, it is important to keep the reliability indicators at good levels [21].

3.1. Reliability indicators

The calculation of the reliability indicators are values that synthesize statistical aggregates, which can be calculated from the historical interruptions that occur in certain regions or groups of consumers of the distribution system [22, 23].

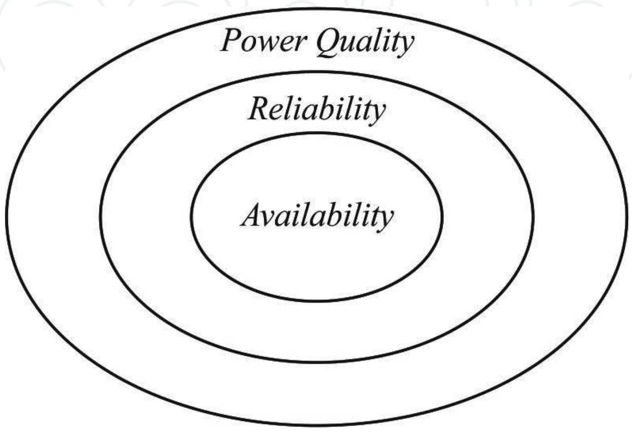

Figure 3. Power quality and subgroups.

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The main reliability indicators are defined in the guide [24], among which the most used are:

- SAIFI—System average interruption frequency index: This index considers the number of interruptions on a media that consumer or a group or consumers suffer during a period.

$$\text{SAIFI} = \frac{\sum_i N_i}{N_T} \tag{4}$$

where

N_i: number of consumer units affected at each interruption; and

N_T: total number of consumer units of the group.

- SAIDI—System average interruption duration index: This index considers the duration of the interruptions, thus having an average of hours that a given consumer has his energy supply interrupted during the period.

$$\text{SAIDI} = \frac{\sum_i (r_i \cdot N_i)}{N_T} \tag{5}$$

where

N_i: number of consumer units affected at each interruption;

r_i: duration of each interruption; and

N_T: total number of consumer units of the group.

- ENS—Energy not supplied index: This index relates the total of energy not supplied in all group due interruptions in all the events in a given period.

$$\text{ENS} = \sum_i r_i \cdot L_i \tag{6}$$

where

r_i: duration of each interruption; and

L_i: energy not supplied in each interruption.

3.2. Modeling of reliability in distribution networks

To model the distribution network to calculate its reliability, it is important to be aware that there may be faults that impact different amounts of customers, such as an external fault that affects all consumers or a one fault on a transformer or in a point of the network that only affects a small group [25]. Then there will be faults with different levels of comprehensiveness.

For this modeling, there are different methods such as block classification and analytical simulation [26] and the logic-structural matrix (LSM). The method that best fits with the protection equipment is the logic-structural matrix, due to the presence of the maneuverable equipment installed in the network, on the different groups of consumers. By switching, the equipment can isolate faults with consumers, or reestablish them, based on the maneuvers allowed for fault isolation and network reconfiguration.

The logic-structural matrix is composed of the main data of the following:

- *Annual failure rate* (λ): This media is obtained through the history of failures of that group.
- *Mean time to restore power supply* (*TR*): This measure is the average time of the restoration of the energy supply, this time is composed of several phases such as the time of displacement of the maintenance team, time of repair, and even the time of waiting between the event of the failure and the authorization of the displacement of the maintenance team
- *Number of customers* (*N*): It refers properly to the number of consumers fed in that region, being able to be fed by transformers or directly connected in the primary network.
- *Load active power* (*L*): Active load, transformers or consumers connected directly to the primary network.

The LSM is composed as follows: the columns are equivalent to the protection or switching equipment of the system and each row is equivalent to the points of the system (these points can be divided according to the needs of the company; they can be transformers, primary consumers or networks extensions). In the cells of the logical-structural matrix, there are initial values of the mean time to power restoration. In order to define these values, it is required to analyze how long it takes to restore the power supply for the corresponding consumers (matrix line), when they are faced with a failure in the distribution network assuming the protective and switching equipments installed on the network (matrix column) [27, 28].

In the presence of switching equipment, one must evaluate the possibilities for switching, isolating defects or transferring loads through these devices. The first possibility is sectionalizing, what corresponds to the isolation of the segment under failure and other associated nodes downstream of a normally closed (NC) from nodes upstream. The mean time to isolate (TI) is computed for consumers on all these upstream nodes. The second option is the transfer of the nodes downstream from the NC switch; when an upstream fault occurs, then the mean time to transfer (TT) is considered for the consumers downstream. The last possibility depends on the existence of a normally open (NO) switch downstream from the NC, and the adjacent feeder must have available technical capacity to receive the loads that will be transferred. For manual switches, the TI and TT also include: mean time of wait (TW) and mean time to travel (TTr). For automatic switches, the TI and TT are much shorter, because there are not TW and TTr. Normally TR > TT > TI.

The protection devices prevent upstream faults or defects from affecting the nodes in downstream of the device. This way, downstream nodes do not have their power supply interrupted, then in the cells of LSM, in these nodes can be placed the number 0.

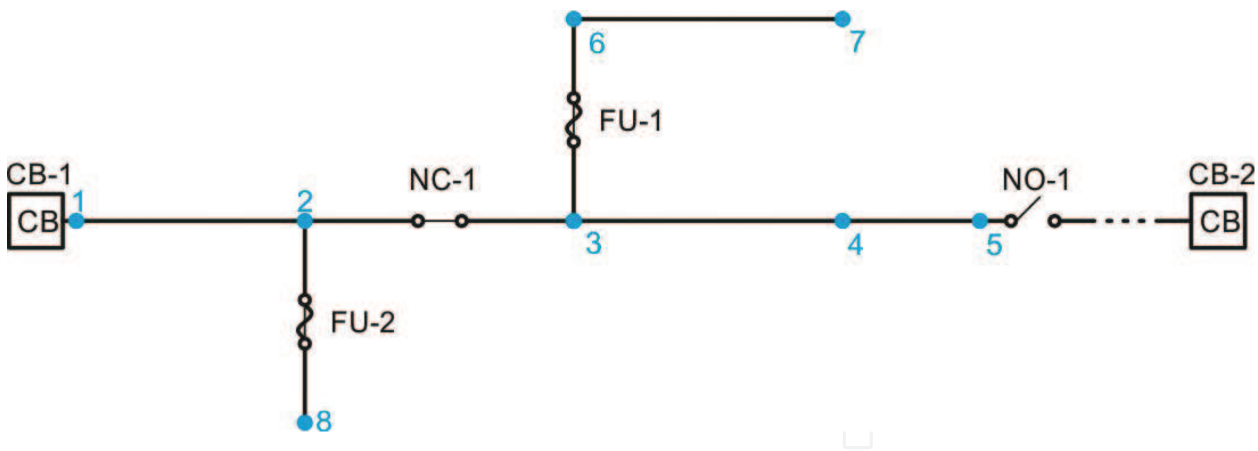

Figure 4. Example distribution network.

To illustrate, the logical-structural matrix for the simplified distribution network is shown in **Figure 4**. It is assumed that the NO switch at node 5 is connected to another feeder with the technical capability to receive loads downstream of the NC switch.

Table 1 shows the construction of logical-structural matrix for the example in **Figure 4**, considering the mean time to power restoration of node *i* (TR*i*), and constants time to isolation (TI), and time to transfer (TT) for each device.

One can note that, for the outage of the circuit breaker (CB-1), the total time to restore power for all consumers is computed, except to those downstream of the NC switch, for which the transfer time to another feeder is considered. For failures downstream of the NC switch, the time to isolate the fault for upstream consumers of the switch and the total time to restore

Nodes (distribution transformers or primary customers)	Protective and switching equipment			
	Circuit breaker CB-1	Switch NC	Fuse FU-1	Fuse FU-2
1	TR1	TI	0	0
2	TR1	TI	0	0
3	TT	TR2	0	0
4	TT	TR2	0	0
5	TT	TR2	0	0
6	TT	TR2	TR3	0
7	TT	TR2	TR3	0
8	TR1	TI	0	TR4

Table 1. Logical-structural matrix to the distribution network of **Figure 4**.

power to its downstream customers is computed. Regarding the outage of fuses (FU-1 and FU-2), 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 matrix values are multiplied by the failure rate of the respective equipment (λi), as shown in **Table 2**.

The reliability index is then calculated from the LSM. To calculate the expected value of SAIDI, the terms of each row of **Table 2** are added and then multiplied by the respective amount of consumers in that row, and then the results of all lines are added together and divided by the total number of customers served [28], as follows:

$$\text{ESAIDI} = \frac{\sum_{i=1}^{n}\left(\sum_{j=1}^{m} M_{i,j}\right)\cdot N_i}{N_C} \tag{7}$$

where

ESAIDI = expected value of system average interruption duration index (h/year);

$M_{i,j}$ = element in row i and column j of LSM;

Ni = number of consumers for the row i;

N_C = total number of customers served;

n = number of rows; and

m = number of columns.

Nodes (distribution transformers or primary customers)	Protective and switching equipment			
	Circuit breaker CB-1	Switch NC	Fuse FU-1	Fuse FU-2
1	TR1 $\lambda 1$	TI $\lambda 2$	0	0
2	TR1 $\lambda 1$	TI $\lambda 2$	0	0
3	TT $\lambda 1$	TR2 $\lambda 2$	0	0
4	TT $\lambda 1$	TR2 $\lambda 2$	0	0
5	TT $\lambda 1$	TR2 $\lambda 2$	0	0
6	TT $\lambda 1$	TR2 $\lambda 2$	TR3 $\lambda 3$	0
7	TT $\lambda 1$	TR2 $\lambda 2$	TR3 $\lambda 3$	0
8	TR1 $\lambda 1$	TI $\lambda 2$	0	TR4 $\lambda 4$

Table 2. Logical-structural matrix with times versus failure rate.

The expected value of ENS is straight forward obtained by replacing the number of consumers in Eq. (8) by its respective load, active power of the distribution transformers, ignoring the total number of customers served

$$\text{EENS} = \sum_{i=1}^{n}\left(\sum_{j=1}^{m} M_{i,j}\right)\cdot L_i \tag{8}$$

where

EENS = expected value of energy not supplied (kWh/year);

$M_{i,j}$ = element in row i and column j of LSM;

L_i = average load, maximum demand of active power multiplied by the respective load factor, associated to row i (kW);

n = number of rows; and

m = number of columns.

To obtain the expected value of SAIFI, the process is similar to the SAIDI, requiring only replacement of the logical-structural matrix average times (TR, TI, and TT) by 1, so are considered only the failure rates.

$$\text{ESAIFI} = \frac{\sum_{i=1}^{n}\left(\sum_{j=1}^{m} M^{*}_{i,j}\right)\cdot N_i}{N_C} \tag{9}$$

where

ESAIFI = expected value of system average interruption frequency (failures/year);

$M^{*}_{i,j}$ = element in row i and column j of LSM, without considering the mean times;

N_i = number of customers for the row i;

N_C = total number of customers served;

n = number of rows; and

m = number of columns.

4. Assessment of protection considering the reliability

In order to evaluate the influence of protection on the reliability of the distribution system, the methodology is shown in the flowchart of **Figure 5** can be used. This generic model seeks that the protection devices can be adjusted for both coordination and selectivity quality. For a better understanding of how the impact of selectivity and coordination on reliability will be, we have an example below, the circuit is shown in **Figure 6**.

Considering a theoretical system, we have the base network shown in **Figure 5** and having the following considerations in the protection:

- *Circuit breaker* (CB-1): It is selective for short circuits in all nodes of the network.
- *Recloser* (R-1): It is selective for short circuits between nodes 4 and 5.
- *Fuse* (FU-1): It is selective for short circuits between nodes 8 and 9.
- *Fuse* (FU-2): It is selective for short circuits between nodes 6 and 7.

Faults may occur with transient (momentary) character as being sustained (permanent) [29]. With the coordination of protection devices, in addition to avoiding a complete shutdown of the system, the effect of transient faults on the network can be reduced through the reclosers. The transient faults are most of the faults that occur in the distribution network, reaching values between 80 and 90% of total faults [30]. To better illustrate this, two LSMs can be established, one for sustained faults (**Table 3**) and the other for momentary faults (**Table 4**).

With the idea of visualizing the impact of device coordination and selectivity on reliability, a simple change that could be implemented would be to selectively the R-1 device for nodes 6 and 7 together with the coordination between the R-1 device and FU-2. With these changes, we would have the following result in the sustained LSM (**Table 5**) and momentary LSM (**Table 6**).

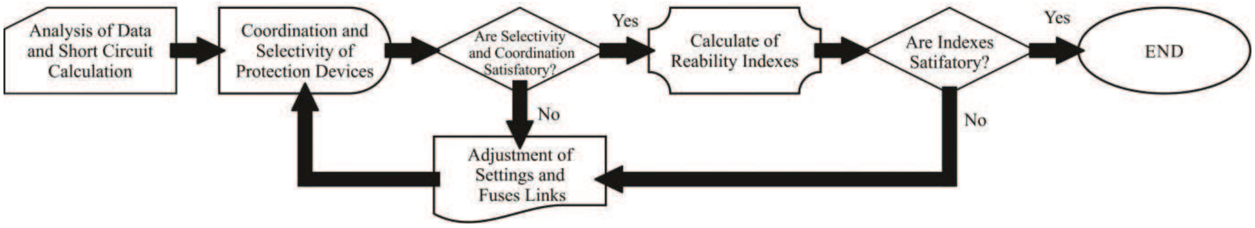

Figure 5. Methodology of assessment of protection and reliability.

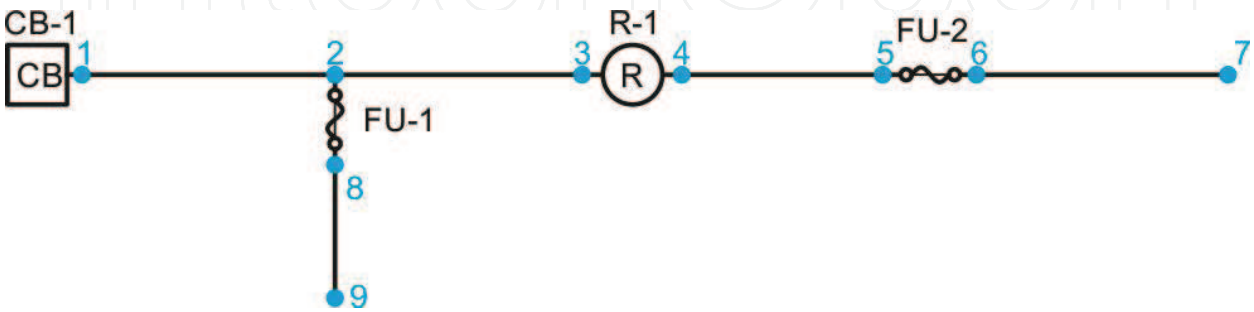

Figure 6. Example distribution network.

Nodes	Protective equipment			
	Circuit breaker CB-1	**Recloser R-1**	**Fuse FU-1**	**Fuse FU-2**
1	TR1 λ_{P1}	0	0	0
2	TR1 λ_{P1}	0	0	0
3	TR1 λ_{P1}	0	0	0
4	TR1 λ_{P1}	TR2 λ_{P2}	0	0
5	TR1 λ_{P1}	TR2 λ_{P2}	0	0
6	TR1 λ_{P1}	TR2 λ_{P2}	0	TR4 λ_{P4}
7	TR1 λ_{P1}	TR2 λ_{P2}	0	TR4 λ_{P4}
8	TR1 λ_{P1}	0	TR3 λ_{P3}	0
9	TR1 λ_{P1}	0	TR3 λ_{P3}	0

Table 3. Initial LSM considering sustained faults.

Nodes	Protective equipment			
	Circuit breaker CB-1	**Recloser R-1**	**Fuse FU-1**	**Fuse FU-2**
1	TR1 λ_{M1}	0	0	0
2	TR1 λ_{M1}	0	0	0
3	TR1 λ_{M1}	0	0	0
4	TR1 λ_{M1}	TA2 λ_{M2}	0	0
5	TR1 λ_{M1}	TA2 λ_{M2}	0	0
6	TR1 λ_{M1}	TA2 λ_{M2}	0	TR4 λ_{M4}
7	TR1 λ_{M1}	TA2 λ_{M2}	0	TR4 λ_{M4}
8	TR1 λ_{M1}	0	TR3 λ_{M3}	0
9	TR1 λ_{M1}	0	TR3 λ_{M3}	0

TA2: Reclosing action time, considering the ability to disconnect and reconnect the circuit with the reclosing device, thus decreasing the shutdown time (TR > TA).

Table 4. Initial LSM considering momentary faults.

In short, under the conditions of permanent failure, the system would keep practically the same levels in the reliability indicators. The main impact would be directly on the temporary faults, where for faults in nodes 6 and 7 the re-establishment time would now be only the recloser R-1, no longer the replacement time of the FU-2 fuse. This impact would be strongly noticed in the SAIDI indicator, which considers the duration of faults.

Nodes	Protective equipment			
	Circuit breaker CB-1	Recloser R-1	Fuse FU-1	Fuse FU-2
1	TR1 λ_{P1}	0	0	0
2	TR1 λ_{P1}	0	0	0
3	TR1 λ_{P1}	0	0	0
4	TR1 λ_{P1}	TR2 λ_{P2}	0	0
5	TR1 λ_{P1}	TR2 λ_{P2}	0	0
6	TR1 λ_{P1}	TR2 λ_{P2}	0	TR4 λ_{P4}
7	TR1 λ_{P1}	TR2 λ_{P2}	0	TR4 λ_{P4}
8	TR1 λ_{P1}	0	TR3 λ_{P3}	0
9	TR1 λ_{P1}	0	TR3 λ_{P3}	0

Table 5. Final LSM considering sustained faults.

Nodes	Protective equipment			
	Circuit breaker CB-1	Recloser R-1	Fuse FU-1	Fuse FU-2
1	TR1 λ_{M1}	0	0	0
2	TR1 λ_{M1}	0	0	0
3	TR1 λ_{M1}	0	0	0
4	TR1 λ_{M1}	TA2 λ_{M2}	0	0
5	TR1 λ_{M1}	TA2 λ_{M2}	0	0
6	TR1 λ_{M1}	TA2 λ_{M2}	0	TA4 λ_{P4}
7	TR1 λ_{M1}	TA2 λ_{M2}	0	TA4 λ_{P4}
8	TR1 λ_{M1}	0	TR3 λ_{M3}	0
9	TR1 λ_{M1}	0	TR3 λ_{M3}	0

Table 6. Final LSM considering momentary faults.

5. Conclusions

In this chapter, the main issues of reliability in the electric power supply as well as the characteristics and adjustments in coordination and selectivity of protection devices were presented, as well as a brief evaluation of their direct impact on the reliability indicators. In addition, it became clear how important it is to keep reliability levels in the pattern for both operational and financial issues. Finally, it is possible to see a theoretical example where the influence of the protection system on reliability was exposed, where, with the coordination and selectivity of a recloser, a great part of the impact of the temporary faults of a circuit can be

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reduced. The result, although theoretical, contributed to the validation of the importance of coordination and selectivity of the protection devices of an energy distribution network. This study can contribute directly in the two target areas of the power utilities, since it brings a broad vision of the system, besides the description of a way to model the network and to calculate the main indicators of reliability.

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