A Fast Directional Overcurrent Relay Coordination Method for Smart Grid Protection

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***Abstract*— Modern power systems are dynamic and complex. Likewise, smart grids bring opportunities for the development of protection relays, such as the ability to communicate remotely. Based on these opportunities, this paper proposes a method of coordinating directional overcurrent relays capable of quickly obtaining the optimal adjustment of the relays with each topological change in the network. The proposed methodology is applied in different cases to a test system, demonstrating its effectiveness and potential.**

***Keywords*— Power transmission; Power system protection; Power systems.**

I. INTRODUCTION

The coordination of devices is one of the most important characteristics in a protection scheme. Events such as the loss of lines can have a significant impact on the capacity to service the network load and, for example, if the coordination of devices has been planned considering only a single scenario, after disconnection of the line, there may be a loss of coordination or even the improper performance of other devices due to the redistribution of load currents. The socioeconomic impact caused by an eventual unnecessary disconnection from the system justifies the adoption of more restrictive reliability criteria. In Brazil, the National Electric System Operator (ONS) adopts, for the operation of the National Interconnected System (SIN), the n-1 reliability criterion, according to which the system must be adjusted to support the loss of some element without interrupting supply to others [1]. In the main trunks of the system, criterion n-1-1 is adopted, which involves the loss of two components. The same criterion is also adopted by other countries, such as the United States [2]. With the adoption of these criteria the protection scheme becomes more robust, as a counterpart, sensitivity in the protection scheme is lost and some devices may have a high operating time for certain topologies of the electrical system.

In the scope of protection of transmission lines, a sudden increase in current is a common indicator of abnormality, consequently, overcurrent protection is widely used [3]. The settings of the overcurrent relays are determined from studies of short-circuits in steady state and aim to maintain the coordination and selectivity of the protection system. In radial network topologies, overcurrent relays operate from a certain level of current regardless of its direction. However, in meshed network topologies with multiple sources, the use of directional overcurrent relays - which act for a given current level in only one direction - makes it possible to discriminate the zone in which the fault occurs, keeping the others with uninterrupted supply.

The coordination process for these topologies is a complex problem since the same relay can be the main protection device in one situation and the backup device in others. In order to facilitate the solution of the coordination problem, it was modeled as an optimization problem [4]. However, the problem is non-linear, due to the coupling between the current and time adjustment variables, which makes it difficult to obtain the optimal solution due to the presence of local maximums and minimums. Several techniques have been proposed to solve the problem. Heuristic methods, for example, were used because their formulations are not so complex [5]–[7]. However, these methods often require adjustment in their parameters, and may converge to local minimums or maximums, so that convergence to a global minimum or maximum is not guaranteed. Other methodologies propose the use of mathematical programming which, although it has a more complex formulation, is guaranteed to converge to the optimal value [8]–[10]. In most cases, it is used as a technique the discretization of one of the two variables, or both. Thus, the problem becomes linear, being possible to solve it with linear programming methods. In this case, the processing time can be long, due to the number of existing variables due to discretization.

With the advent of digital relays with remote communication capabilities and faster methodologies for solving the coordination problem, the philosophy of adaptive protection [11] emerges, whose objective is to change the settings of the relays automatically in order to adapt to the topological variations of the electrical network and keep the protection system adjusted to the topology in operation.

In the context of this situation, the present work proposes a protection methodology that makes it possible to change the settings for the current network topology. To this end, the methodology considers a smart grid environment, in which there is remote communication between the relays and a supervisory system. The parameterization of the relays is carried out considering the short-circuit values of the current topology, so that the protection scheme is maintained with fast operating times. However, the load current values used in the parameterization are obtained considering the n-1 criterion, *i.e.,* already anticipating the disconnection of some line from the system. In this way, a certain robustness is added to the adjustment and, in case of disconnection of any line, until the protection scheme is readjusted, the relays will not unduly act by redistributing the load currents.

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For the proposed methodology, as the adjustment and coordination of the protection scheme is redone for each change in the network topology, a tool is needed to obtain the adjustments quickly. In this way, Mixed Integer Linear Programming is used as an exact optimization technique to obtain the time and current adjustments of the relays.

Finally, the methodology includes the possibility of failure in communication between the supervisory system and a relay at the time of readjusting its parameters. In this situation, the adjustment and coordination obtained must be recalculated considering the parameters with which the relay with communication failure is set fixed.

II. PROBLEM DESCRIPTION

The curve of operating time *vs* sensitization current for overcurrent relays is defined by standard [12], [13], according to (1).

$$t = TDS \times \left[\frac{\beta}{\left(\frac{I_{relay}}{PCS} \right)^{\alpha} - 1} + L \right] \tag{1}$$

Where t is the operating time of the relay [s]; TDS is the time setting of the relay [s]; PCS is the current setting of the relay [A]; I_{relay} is the input current of the relay [A]; β, α and L are coefficients that define the characteristics of the relay curve defined by standards [12], [13].

It is possible to verify that the operating time of a relay is defined by adjusting its PCS and TDS values. The current setting of the overcurrent relay is set so that the relay does not operate for the maximum load current and operates for the minimum short-circuit current between phases. Factors are included to guarantee these two situations, as (2).

$$a \times I_{L\max} < PCS < \frac{I_{F\min}}{b} \tag{2}$$

Where: PCS is the current setting of the relay [A]; I_{Lmax} is the maximum load current [A]; a is a factor used to ensure that the relay does not operate improperly for brief overload conditions. Normally, values between 1.25 and 2.5 are used; PCS is the current setting of the relay [A]; $I_{F\min}$ is the minimum short-circuit current between phases [A]; b is a factor used to ensure that the relay operates for minimum short-circuit current conditions between phases. Normally, the value of 1.05 is used for applications with digital relays.

The time setting of the overcurrent relay is determined by the coordination between the devices. The purpose of coordination is to ensure that the relay closest to a given fault acts before any existing backup relay, that is, the main relay must have a shorter operating time than the backup relay. It is also necessary to guarantee a minimum time interval between the operation of the main relay and the operation of the backup relay, known as the Coordination Time Interval (CTI). The CTI considers the operating time of the circuit breaker and must be maintained throughout the coordination range between main and backup relays, as (3). The IEEE 242-2001 standard provides a practical recommendation that the CTI be maintained at least 200 ms [14].

$$t_{b_x} - t_p \geq CTI \tag{3}$$

Where: CTI is the Coordination Time Interval [s]; p is the subscript that represents the main relay; b_x is the subscript that represents the x backup relay; t_{b_x} is the operating time of the backup relay [s]; t_p is the operating time of the main relay [s].

III. METHODOLOGY

In the proposed methodology, the overcurrent relay adjustment and coordination problem is formulated as a MILP problem. Considering that the problem of coordination of overcurrent protection is non-linear, due to the existing coupling between the PCS and TDS variables, to formulate it as Linear Programming is necessary to use some linearization device. In this case, the current adjustment is obtained with discrete values and the time adjustment in continuous values.

The objective of the model is to minimize the operation time of each existing relay in the problem in order to maximize safety and minimize possible damage to equipment and system stability, as shown in (4).

$$\min \quad \sum_{i \in I} T_i \tag{4}$$

In which T_i corresponds to the operating time of relay i for a set of I relays present in the problem.

The model restrictions are related to: (a) the operation time of each relay; (b) the minimum coordination time (CTI) between main and backup relays; (c) the limit values for continuous time adjustment; (d) the possibility of choosing only one setting per relay.

The proposed scheme uses the communication capability of digital overcurrent relays so that, with each network topology change, a supervisory system remotely redefines the optimal protection setting. The graphical representation of the methodology is presented by the flowchart of Fig 1. Initially, the network topology is processed by the supervisory system. Then, the short circuit analysis of the current topology is performed, and the fault current values are saved for each main and backup relay pair. Afterwards, the power flow is performed for each of the possible n-1 topologies in the network. The objective is to obtain the highest load current value that would be seen by each relay in an n-1 situation. These maximum load current values are also saved. The saved fault current and maximum load current values for each relay are imported into the MILP model. The model is solved, and the relays are parameterized by the supervisory system according to the solution obtained.

If there is a communication failure between the supervisory system and a given relay, and it is not possible to change the time and current setting of this relay, the supervisory system returns to the MILP model the previous values to which the relay is adjusted as a restriction. Thus, the model is solved so that the other relays, which are with communication working, fit around the relay with a communication problem. In this way, the coordinated protection scheme is maintained until the communication failure between the supervisory system and the respective relay is resolved.

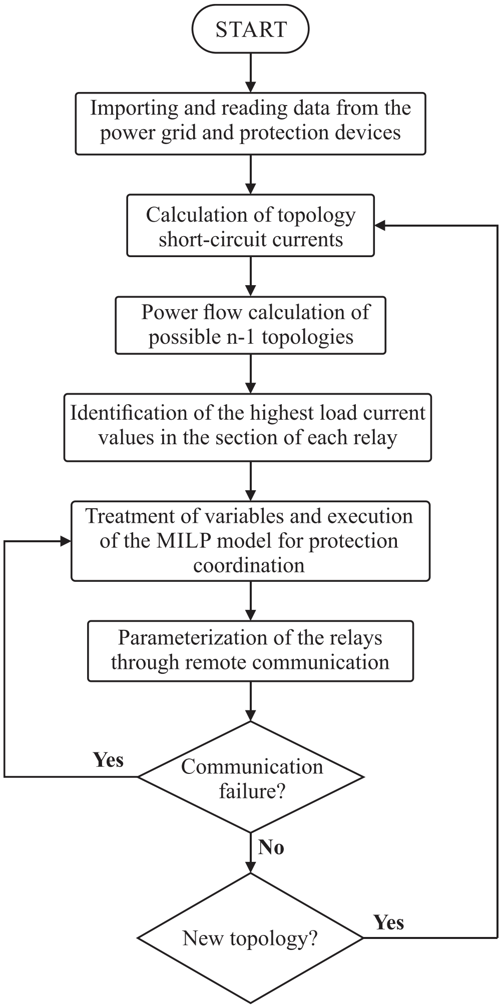

Fig 1. Flowchart of the proposed methodology.

IV. RESULTS

The test system used to implement the methodology is the 8-bus, illustrated by Fig 2. The system consists of 2 synchronous generators operating at 10 kV, 2 transformers with a ratio of 1.500, 7 lines, distributed among the 8 buses, operating at 150 kV and an equivalent system with a short-circuit power of 400 MVA connected to bus 4. The protection scheme of the system consists of 14 directional overcurrent relays [15]. Table I shows the RTC for the 8-bus system relays and Table II shows the fault current values in the main and backup relays for three-phase short-circuits at the beginning of the protection section.

TABLE I. TRANSFORMATION RATIO OF CURRENT TRANSFORMERS OF THE 8-BUS SYSTEM.

Relays	**RTC**
3, 7, 9, 14	160
1, 2, 4, 5, 6, 8, 10, 11, 12, 13	240

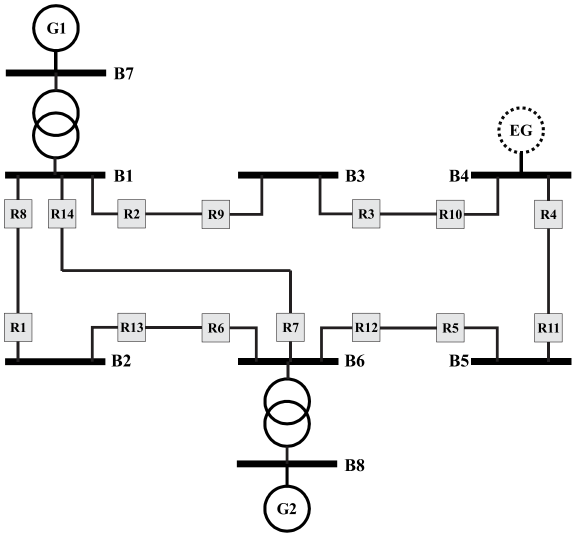

Fig 2. 8-bus test system.

TABLE II. FAULT CURRENTS IN THE MAIN AND BACKUP RELAYS FOR THREE-PHASE SHORT-CIRCUIT AT THE BEGINNING OF THE LINE.

Pair nº	**Main relay**	**Backup relay**	Icc_p **[A]**	Icc_b **[A]**
1	**1**	**6**	3233	3233
2	**2**	**1**	5921	996
3	**2**	**7**	5921	1889
4	**3**	**2**	3556	3556
5	**4**	**3**	3783	2243
6	**5**	**4**	2401	2401
7	**6**	**14**	6109	1873
8	**6**	**5**	6109	1198
9	**7**	**13**	5223	987
10	**7**	**5**	5223	1198
11	**8**	**7**	6091	1889
12	**8**	**9**	6091	1165
13	**9**	**10**	2484	2484
14	**10**	**11**	3884	2345
15	**11**	**12**	3708	3708
16	**12**	**14**	5899	1873
17	**12**	**13**	5899	987
18	**13**	**8**	2990	2990
19	**14**	**1**	5196	996
20	**14**	**9**	5196	1165

For analysis of the methodology, three case studies are performed using the 8-bus test system. In the first case, the methodology proposed in this work is used for the main topology of the test system. Thus, coordination is performed considering the current fault current values and the maximum load current values considering the n-1 criterion. In the second case, the disconnection of a line from the network is considered. According to the proposed methodology, in this situation the adjustment and coordination would be redone considering the fault values of this new topology and the maximum load current values considering criterion n-1 of this new topology (n-2 in relation to the original topology). This case is used to simulate the third case, in which a situation of communication failure between the supervisory system and a relay during the readjustment is simulated. In this situation, the adjustment and coordination are re-done considering the parameters already set for the relay that failed in remote communication fixed. The MILP model was processed using the commercial solver CPLEX® 12.10 on a computer running Windows 10 with Intel Core I5 3.2 GHz and 4 GB RAM. For the adjustment and coordination of the protection system, the following parameters were used:

- Characteristic of the curve: IEC Inverse;
- CTI: 0.3 seconds;
- TDS: Continuous adjustment from 0.1 to 1.1;
- PCS: discrete adjustment from 0.5 to 6.5 with 0.25 step;
- PCS limited in the range between 1.25 times the maximum load current and 2/3 of the minimum fault current between phases.

In case 1, the methodology proposed by this work is used for the main topology of the test system. In this sense, the adjustment and coordination are carried out with the fault current values of the current topology and the maximum load current values considering criterion n-1. The fault current values are shown in Table II.

To obtain the maximum load current values, evaluation of the load currents in each relay for each of the possible n-1 topologies is necessary. In this case, seven possible topologies were evaluated, each of which disconnected one of the lines from the current system and saved the current values obtained through the power flow. Table III gathers the maximum current values seen by each relay in its protection section obtained through criterion n-1.

TABLE III. MAXIMUM LOAD CURRENT IN EACH RELAY OF THE 8-BUS SYSTEM.

Relay nº	$I_{L\max}$ **[A]**	**Relay nº**	$I_{L\max}$ **[A]**
1	111	**8**	248
2	1001	**9**	-
3	786	**10**	280
4	335	**11**	756
5	-	**12**	1001
6	254	**13**	108
7	326	**14**	332

Table IV presents the adjustment values of TDS and PCS for each relay and the value of the objective function, according to the proposed methodology. The processing time to obtain the result was 1.92 seconds. According to Fig 3, the coordination between main-backup pairs of relays is satisfied once CTI ≥ 0.3 s.

TABLE IV. VALUES OF TDS AND PCS FOR EACH RELAY AND OBJECTIVE FUNCTION FOR CASE 1.

Relay	**TDS**	**PCS**
1	0,101906	1,75
2	0,100263	6,50
3	0,100000	6,25
4	0,101962	3,75
5	0,106515	1,75
6	0,101740	4,50
7	0,101394	5,00
8	0,101930	4,25
9	0,100000	2,75
10	0,102189	3,75
11	0,100680	4,00
12	0,101623	6,50
13	0,101901	1,75
14	0,101452	5,00
OF [s]	6,1344	

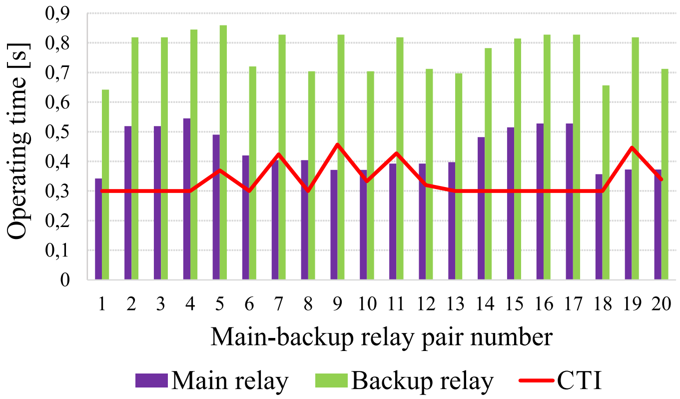

Fig 3. Operating times for Case 1.

Case 2 simulates the proposed methodology after disconnecting a line from the system. In this case, according to the methodology, the adjustment and coordination of the overcurrent relays is redone. The fault current values of this new topology and the maximum load current values are used considering the n-1 criterion, that is, n-2 in relation to the initial topology. Regarding the original topology, the line connecting bars 1 and 6 was disconnected, as shown in Fig 4. Thus, relays 7 and 14 are not in operation. Table V shows the fault current values for the main and backup sets of relay and Table VI shows the maximum current values seen by each relay in its protection section obtained through criterion n-1.

TABLE V. FAULT CURRENTS IN THE MAIN AND BACKUP RELAYS FOR THREE-FASE SHORT-CIRCUIT AT THE BEGINNING OF THE LINE.

Pair nº	**Main relay**	**Backup relay**	Icc_p **[A]**	Icc_b **[A]**
1	**1**	**6**	3186	3186
2	**2**	**1**	5035	1997
3	**2**	**7**	5035	x
4	**3**	**2**	3290	3290
5	**4**	**3**	3792	2252
6	**5**	**4**	2616	2616
7	**6**	**14**	4708	x
8	**6**	**5**	4708	1669
9	**7**	**13**	x	x
10	**7**	**5**	x	x
11	**8**	**7**	4678	x
12	**8**	**9**	4678	1639
13	**9**	**10**	2681	2681
14	**10**	**11**	3875	2335
15	**11**	**12**	3410	3410
16	**12**	**14**	5020	x

17	**12**	**13**	5020	1981
18	**13**	**8**	3036	3036
19	**14**	**1**	x	x
20	**14**	**9**	x	x

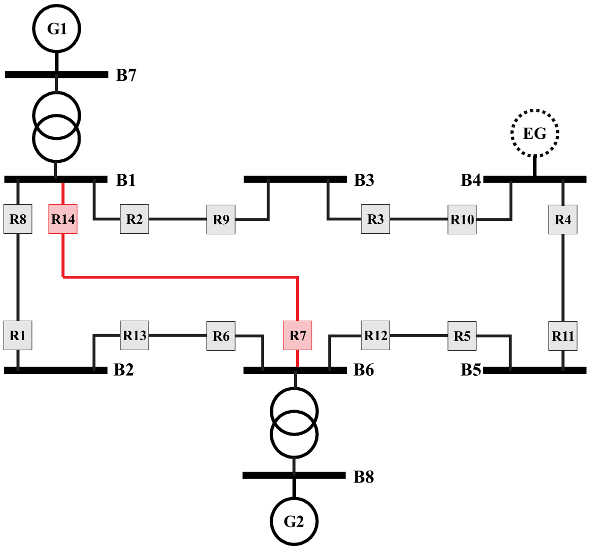

Fig 4. 8-bus test system with the disconnection of the line that connects bus 1 and 6.

TABLE VI. MAXIMUM LOAD CURRENT IN EACH RELAY OF THE 8-BUS SYSTEM.

Relay nº	$I_{L\max}$ **[A]**	**Relay nº**	$I_{L\max}$ **[A]**
1	431	**8**	578
2	1000	**9**	-
3	784	**10**	280
4	335	**11**	755
5	-	**12**	1000
6	578	**13**	432
7	x	**14**	x

Table VII shows the adjustment values of TDS and PCS for each relay and the value of the objective function, obtained through the proposed methodology. The processing time to obtain the result was 0.50 seconds. According to Fig 5, the coordination between main-backup pairs of relays is satisfied once CTI ⩾ 0.3 s.

TABLE VII. VALUES OF TDS AND PCS FOR EACH RELAY AND OBJECTIVE FUNCTION FOR CASE 2.

Relay	**TDS**	**PCS**
1	0,101224	3,75
2	0,101906	6,25
3	0,100045	6,50
4	0,104170	4,75
5	0,106538	3,00
6	0,102870	5,75
7	x	x
8	0,100000	5,75
9	0,102659	4,50
10	0,103434	4,75
11	0,100000	4,50
12	0,101545	6,50
13	0,102369	3,75
14	x	x
OF [s]	6,954	

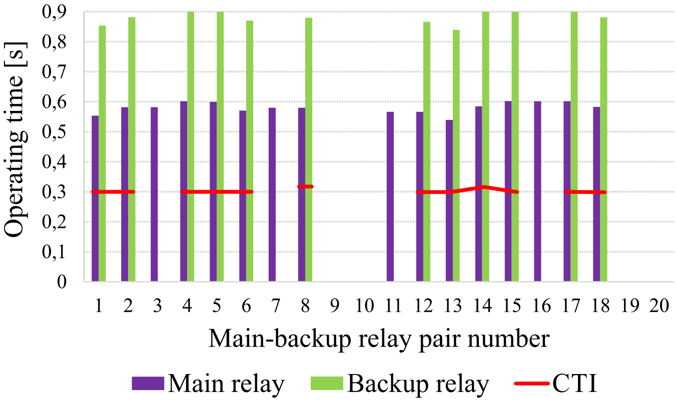

Fig 5. Operating times for Case 2.

The protection readjustment scenario after the disconnection of line 3 is used to simulate a communication failure between a given relay and the supervisory system. In this case, the simulation considers that the network was in its original configuration, with the settings of the relays obtained in Case 1, as shown in Table IV. When line 3 is disconnected, the methodology would act to readjust the relays according to the values obtained in case 2 and shown in Table VII. However, if a communication failure occurs between a given relay and the supervisory system, the parameterization that would be implemented must be recalculated considering the PCS and TDS values to which the relay was previously set fixed, in this case the adjustment values of Case 1. The setting of the relay that must be considered fixed is included as a constraint in the MILP model. As an example, a situation of communication failure between the supervisory system and relay 2 is simulated, whose PCS and TDS values were set at 6.50 and 0.100263, respectively. After disconnection of line 3, the methodology would readjust the PCS and TDS values to 6.25 and 0.101906, respectively. However, due to the communication failure, the previous values are kept fixed and the methodology recalculates the parameters of the other relays. Table VIII shows the PCS and TDS adjustment obtained for the other relays considering the situation of the fixed adjustment of relay 2. According to Fig 6, the coordination between main-backup pairs of relays is satisfied once CTI ⩾ 0.3 s.

TABLE VIII. VALUES OF TDS AND PCS FOR EACH RELAY AND OBJECTIVE FUNCTION FOR CASE 3.

Relay	**TDS**	**PCS**
1	0,102374	3,75
2	0,100263	6,50
3	0,100111	6,50
4	0,104274	4,75
5	0,100000	3,25
6	0,103627	5,75
7	x	x
8	0,100000	5,75
9	0,102659	4,50
10	0,103434	4,75
11	0,100000	4,50
12	0,101545	6,50
13	0,102369	3,75
14	x	x

OF [s]	6,976

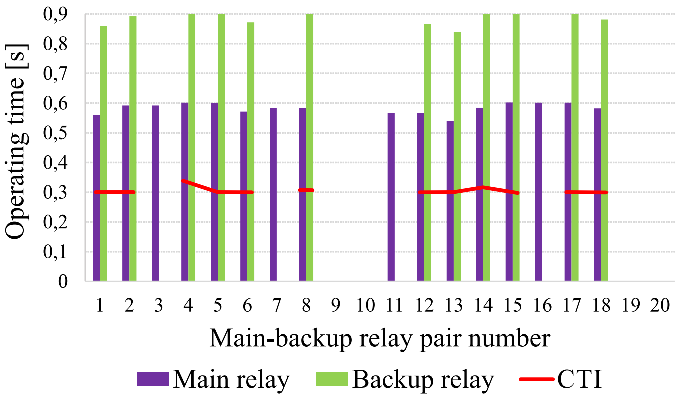

Fig 6. Operating times for Case 3.

It is emphasized that this would be a momentary solution, until the problem of remote communication failure between the supervisory system and the relay is solved. In addition, the methodology will not always find a feasible solution, since it seeks to adjust a protection scheme for a scenario with a relay already adjusted for a different scenario. But when a feasible solution is found, it is an interesting option to keep the system operating safely until the problem is corrected.

V. CONCLUSION

This work proposed an adaptive directional overcurrent protection methodology that considers in advance an n-1 contingency state of the network and that has compatible time performance for real-time applications. In order to have its implementation possible, the scope of smart electrical networks was considered, that is, an integrated electrical network with measuring points, a fast communication network and digital relays with remote communication capacity.

The protection adjustment and coordination problem was modeled as a MILP problem. Given the non-linearity of the problem, the current adjustment variable was discretized as a linearization technique. Thus, the model was formulated in order to obtain the current adjustment discreetly and the time adjustment continuously. As a result of this formulation, a reduced number of variables in the problem is obtained, which results in a fast-processing time, compatible with the application in real time. In the four test cases performed, the results showed the methodology's ability to quickly determine the adjustment and coordination of the protection system and its application potential.

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