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IMPROVING RECLOSER-FUSE COORDINATION WITH SELF-ADAPTIVE ADJUSTMENT

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Abstract— The use of advanced communication and computation technologies, together with the need to make systems more secure and reliable, pushes for the development of new methods of protection that take into consideration new features. However, the advances must reconcile with analog equipment already present in the protection systems, such as fuses. In this sense, this work proposes the development of a self-adjusting recloser, aiming at efficient coordination with the fuse involved in the fault. For this purpose, the automatic reconfiguration of the Time Dial (TD) of the delayed characteristic curve of the recloser is carried out based on the current measurements obtained in the fuse involved in the short circuit. The proposed method provides significant reductions in operating times due to the recloser delayed characteristic curve, which, in turn, reduces the chances of damages to the system components.

Keywords— Recloser; Fuse; Self-adaptive; Distribution System; Coordination.

1 Introduction

The growing demand, as well as the requirement of more reliable electrical systems, have led to the development of more complex distribution systems that takes into account local generation and reliable delivery to the customers. In order to ensure the quality of the electricity services, the monitoring of several parameters by the regulatory agencies, among which, the continuity of service stands out. The protection system is mainly responsible for dealing with safety and also with the continuity of service. Therefore, protection systems must have the necessary means to ensure the sensitivity and reliability, in order to protect large areas (coordination and selectivity) with short response time to short circuits.

Among the various protection devices, reclosers and fuses are the most used in Distribution Systems (DSs). Due to their simplicity and cost/benefit, the fuses are utilized in larger quantities in the DSs. However, because of their operating nature, coordination with other equipment can become not so efficient.

With the advent of the internet of things (it makes the equipment capable of interacting and cooperating with each other (Atzori et al., 2010)), and with the 5G communication technology (it allows high data rate with low latency (Andrews et al., 2014)), the self-adjustment of the protective devices based on the measurements and communications performed by them becomes a reality (Tang and Yang, 2017; Zhang et al., 2013).

In this context, the main objective of this work is to analyze the performance of a self-adaptive recloser for different types of short circuits. As a requirement, the recloser features local processing. As input, it requires information about the currents that flow through the other protective equipment (fuses). Such mode of operation allows the recloser to self-adjust, taking into account other equipment that has a fixed adjustment without human intervention. Both the recloser and the fuse have been modeled by the PSCAD™/EMTDC™ software, which allows simulations in the time domain.

As can be seen in the review by Singh (2017), most papers disregard the use of reclosers and fuses and consider only the presence of overcurrent relays. In the context of the use of reclosers and fuses, the work of Naiem et al. (2012) implements a classification technique to determine the state of coordination between fuse reclosers during the insertion of the Distributed Generation (DG). Therefore, if there is no coordination, two actions are recommended: finding a better location for the DG or changing the recloser settings. The work of Dawoud et al. (2017) proposes two solutions for the adaptive adjustment of the recloser. The first one, offline, can be applied when there are no frequent changes in the DS. In that method, the recloser has two categories of adjustments: one for the presence of DG and another one for the absence of it. The second one, online, is adopted when DGs are frequently connected to the system. In this case, the maximum fault current seen by the recloser and the fuse is determined through a short circuit analysis. With these values, the recloser Time Dial (TD) is adjusted to the new topology.

Based on the earlier papers and observing similar ones, most of them do not consider reclosers and fuses simultaneously, or when they do, they do not have an adjustment based on the existing protective equipment involved in the fault. Thus, the main contribution of this paper is to present an automatic adjustment of the TD of the recloser based on the fuse involved in the short-circuit. This adjustment allows reducing, significantly, the operating times of the recloser delayed characteristic curve.

This paper is organized as follows: Section 2 presents the conventional coordination between the recloser and fuse. Section 3 presents the proposed methodology for the self-adaptive adjustment of the recloser. Section 4 presents the test system and simulated scenarios. Section 5 presents the results obtained. Finally, the conclusions are presented in Section 6.

2 Conventional Recloser-Fuse Coordination

The coordination criterion between recloser-fuse depends on the allocation of these devices. Usually, the recloser is located near the substation and is a backup of the fuse. In this situation, there are two coordination philosophies: the first, known as fuse-saving, the recloser acts for temporary faults, and the fuse for permanent short-circuits; the second, fuse-blowing, the fuse blows for any fault that occurs in the DS (Gers and Holmes, 2011).

For the fuse-saving philosophy to be adopted, the recloser must have two modes of operation: a fast operation, responsible for opening the circuit, in situations of temporary faults, before the fuse melts; and a delayed operation, which serves as a backup of the fuse for permanent short circuits. Therefore, the minimum fuse curve must be above the fast characteristic curve of the recloser, while the maximum interruption curve of the fuse must be below the delayed characteristic curve. Besides, in order to obtain a correct sequence of operation, it is necessary to observe these rules for the entire fault current range of the feeder.

In order to obtain the highest TD of the fast characteristic curve and the shortest TD of the delayed characteristic curve of the recloser, both fault currents, minimum ($I_{f_{min}}$) and maximum ($I_{f_{max}}$), seen by the recloser and fuse must be considered. Thus, the maximum recloser operating time (t_{max_r}) for the fast characteristic curve is given by (1).

$$t_{max_r} = t_{min_{f|I_{f_{max}}}} - CTI \tag{1}$$

where t_{min_f} is the shortest operating time of the fuse link, and CTI is the coordination time interval, usually 200 ms (Mamede Filho and Mamede, 2011).

In this way, the TD of the fast characteristic curve can be obtained via (2), considering the IEC 60255-151 standard (IEC, 2009).

$$TD_{fast} = \frac{t_{max_r} \times \left[\left(\frac{I_{f_{max}}}{I_p} \right)^{k_2} - 1 \right]}{k_1} \tag{2}$$

where I_p is the pick-up current of the recloser, and k_1 and k_2 are the terms that define the operating curve.

Likewise, the minimum operating time (t_{min_r}) of the recloser delayed characteristic curve is given by (3).

$$t_{min_r} = t_{max_{f|I_{f_{min}}}} + CTI \tag{3}$$

where t_{max_f} is the longest operating time of the fuse link.

Similarly, the TD of the delayed characteristic curve can be obtained via (4). It should be noted that the recloser TDs must be set for all fuses found downstream (Fig. 1).

$$TD_{delayed} = \frac{t_{min_r} \times \left[\left(\frac{I_{f_{min}}}{I_p} \right)^{k_2} - 1 \right]}{k_1} \tag{4}$$

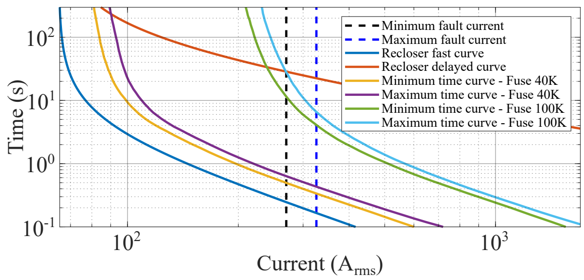

Figure 1: Typical coordination between recloser and fuses.

3 Proposed method

The recloser coordination, based on all downstream fuses, can result in a very high TD for the delayed characteristic curve. In this way, the automatic adjustment of the recloser TD aims to decrease the operating time of the device based on the fault branch protection fuse, as shown in Fig. 2.

Therefore, the current flowing through the fuse, at the time of the fault, must be determined. In this paper, the presence of a current meter, with communication capacity, installed next to the fuse, is being considered for this purpose.

At the instant of the short-circuit, the recloser is sensitized and requests, online and through a communication channel, the current information of the meters located on the fuses. With this information, the recloser, based on a microprocessor, determines whether the fault is downstream of a fuse or not. Besides, the current measurements, together with the knowledge of the type of fuse installed in the fault branch, allow calculating the maximum expected fusing clearance time (using fuse curve interpolation). Then, the TD

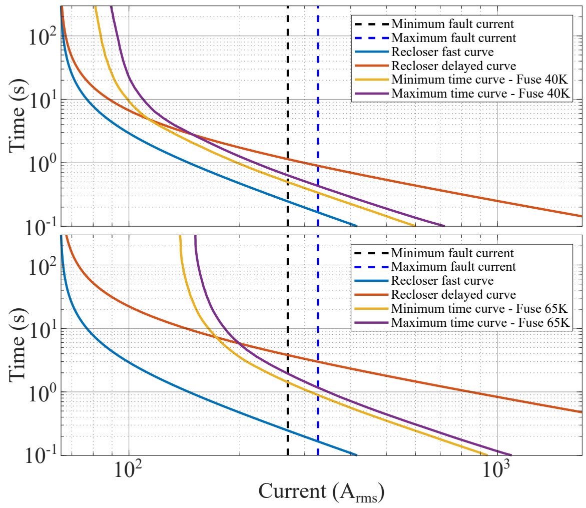

Figure 2: Adaptive recloser coordination based on the fault branch protective fuse.

of the recloser delayed characteristic curve is adjusted based on (3) and (4). The steps described are shown in the flowchart illustrated in Fig. 3.

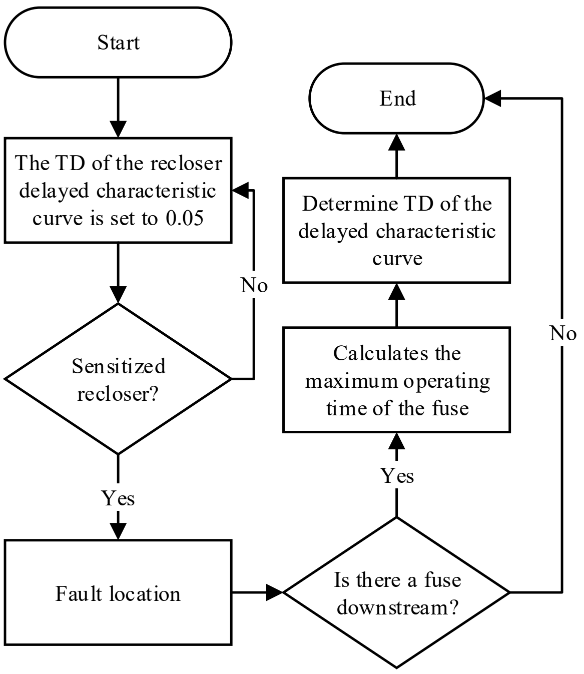

Figure 3: Flowchart of the proposed technique.

As for the TD of the fast-acting curve, it was set at the lowest value (0.05), which guarantees fuse-saving coordination. Due to the adoption of this philosophy, it is possible to locate the fault and adjust the TD, of the delayed characteristic curve, during the reclosing time, which can vary from 0 to 120 s (Mamede Filho, 2013). This allows a communication channel with higher latency to be used, in addition to not impairing, in case of loss of communication, the fast tripping of the recloser, causing, at most, a recloser block without blowing the fuse.

4 Methodology

This section presents a description of the adopted test system, as well as the applied short-circuit scenarios. Also, the allocation of protection devices is presented, along with the adopted parameters.

4.1 Distribution test system

The simulations were performed using the IEEE 34-bus real distribution test system (Fig. 4). The system has approximately a total of 1.69 MVA of connected load, the vast majority in 24.9 kV, with only 416 kVA connected at 4.16 kV. It has two regulators with fixed tap and a power transformer (1.5 MVA, 24.9 kV/4.16 kV), located at bus 832. Finally, it is an unbalanced system with loads of constant power, current, and impedance. It should be noted that the substation transformer has not been considered. More information can be found in (IEEE, 2010).

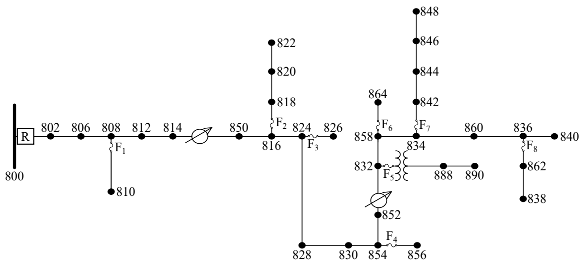

Figure 4: Distribution system 34-bus.

Eight fuses and one recloser, allocated according to Fig. 4, were modeled in the PSCAD™/EMTDC™software. Table 1 shows the nominal current values for each fuse. The data for these devices, for interpolation, were obtained from S&C ELECTRIC COMPANY (2019).

Table 1: Nominal current of allocated fuses

Fuse	Nominal current	Fuse	Nominal current
F1	100K	F5	30K
F2	50K	F6	30K
F3	50K	F7	40K
F4	40K	F8	40K

In order to make a comparison between the operations of the recloser, two adjustments were modeled. The first, with both TDs, of the characteristic curves, fixed and the second with the TD, of the delayed characteristic curve, self-adjusted. In both models, the fast characteristic curve was parameterized based on the data of the extremely inverse curve (IEC, 2009) and TD equal to 0.05. The delayed characteristic curve was parameterized based on the data from the long-time inverse curve (IEC, 2009), and TD depends on the model adopted (0.75 for the fixed model). Besides, the pick-up current was set to 65 A.

4.2 Applied short circuits

Three-phase, three-phase to ground, two-phase, two-phase to ground and single-phase faults were applied, when possible, in the bus 806, 810, 818, 820, 822, 826, 828, 856, 888, 890, 864, 842, 844, 846, 848, 860, 862, and 838, totaling 18 fault locations. The fault resistance was varied by 0.01 Ω, 5 Ω, 20 Ω, and 40 Ω. Therefore, in general, 472 short circuits were applied in the test system.

An interface with PSCAD™/EMTDC™ via Python language was implemented. Thus, the simulation variables (type, location, and resistance) were automatically modified to generate the simulation set. At each simulation, the operating times of the protection devices involved in the fault were obtained. The recloser TD for the second model was also obtained. It is worth mentioning that the loads were automatically converted to constant impedance, by the PSCAD™/EMTDC™ software, when the voltage on the bus is below 0.8 pu.

5 Results

The following subsections present the results obtained for the two models adopted: TD, of the delayed characteristic curve, fixed and self-adjusted.

5.1 Fixed adjustment

In this subsection, the results obtained for the recloser with fixed TD will be presented. In this case, a TD of 0.05 was adopted for the fast characteristic curve and 0.75 for the delayed characteristic curve.

Table 2 shows the recloser operating times, with fixed adjustment, for single-phase short circuits (phase B to ground - BG) with a resistance of 40 Ω. Table 3 shows the operating times of the fuses for the same type of fault. It is possible to verify, in Table 2, that the operating time, because of the delayed recloser characteristic, is very high. This is due to the use of the TD of 0.75. However, this parameterization was necessary due to the maximum fuse clearance time of the fuse F1 for the fault at bus 810. Finally, it should be noted that both the recloser and the fuse were not sensitized to this type of fault at bus 888 and 890.

As can be seen in Table 4, the *CTIs* were above 200 ms for all applied faults. However, there is a long time interval between the delayed recloser actuation and the maximum clearance time of the fuse. This long time can have consequences for the electrical system, because of the permanence of the short circuit for a long time, in case of failure in the fuse operation.

Table 2: Recloser tripping times, with fixed setting, for BG faults with resistance of 40 Ω

Fault location	Fast time (s)	Delayed time (s)
806	0.1762	17.1491
810	0.2486	23.3011
826	0.4483	37.3624
828	0.4370	36.6327
856	0.6775	51.1639
888	-	-
890	-	-
842	0.7629	56.0218
844	0.7700	56.4205
846	0.7884	57.4481
848	0.7911	57.5950
860	0.7714	56.4977
862	0.7859	57.3105
838	0.8093	58.6139

- Not sensitized

Table 3: Fuse actuation times for BG faults with resistance of 40 Ω

Fault location	Fuse	Minimum time (s)	Maximum time (s)
810	F1	9.6847	21.6726
826	F3	2.3294	3.1698
856	F4	2.4608	3.3377
888	F5	-	-
890	F5	-	-
842	F7	2.8748	3.8977
844	F7	2.9282	3.9762
846	F7	3.0630	4.1847
848	F7	3.0819	4.2141
862	F8	3.4952	4.9026
838	F8	3.6842	5.2534

- Not sensitized

Table 4: *CTI* between fixed adjustment recloser and fuse, for BG faults with resistance of 40 Ω

Fault location	*CTI* between fast time & minimum time (s)	*CTI* between maximum time & delayed time (s)
810	9.4361	1.6285
826	1.8811	34.1926
856	1.7834	47.8262
842	2.1118	52.1240
844	2.1582	52.4443
846	2.2746	53.2634
848	2.2909	53.3809
862	2.7093	52.4079
838	2.8749	53.3605

Tables 5 and 6 show the operating times of the recloser and the fuses, respectively, for an ABC fault with an impedance of 0.01 Ω. In this case, it is possible to observe that both the recloser and the fuse were sensitized to the fault at bus 888 and 890. Also, as can be seen in Table 7, the CTI between the minimum melting time of the fuse and the recloser fast operation time was close to the minimum value (200 ms). However, when comparing the maximum clearance time of the fuse with the delayed operating time of the recloser, very high intervals, again, are obtained.

Table 5: Recloser tripping times, with fixed setting, for ABC faults with resistance of 0.01 Ω

Fault location	Fast time (s)	Delayed time (s)
806	0.0859	5.7110
828	0.1970	18.8795
888	0.3521	30.8019
890	1.2777	83.3696
842	0.2732	25.0583
844	0.2759	25.2662
846	0.2834	25.8368
848	0.2845	25.9189
860	0.3474	30.4871
862	0.2828	25.7937

Table 6: Fuse actuation times for ABC faults with resistance of 0.01 Ω

Fault location	Fuse	Minimum time (s)	Maximum time (s)
888	F5	0.5581	0.7078
890	F5	4.9068	8.5590
842	F7	0.6286	0.8120
844	F7	0.6392	0.8254
846	F7	0.6668	0.8602
848	F7	0.6707	0.8651
862	F8	0.6638	0.8574

Table 7: CTI between fixed adjustment recloser and fuse, for ABC faults with resistance of 0.01 Ω

Fault location	CTI between	
	fast time & minimum time (s)	maximum time & delayed time (s)
888	0.2060	30.0941
890	3.6291	74.8106
842	0.3555	24.2462
844	0.3633	24.4408
846	0.3834	24.9766
848	0.3862	25.0538
862	0.3810	24.9363

Table 8 shows the mean values and standard deviations of the $CTIs$ between the fast operation time of the recloser and the minimum fuse melting time for all types of applied faults and resistance in the system test. It is noticed that in most cases, the mean time difference was below 1 s, with some cases showing considerable standard deviations.

Table 9 shows the mean values and standard deviations of the $CTIs$ between the delayed operation time of the recloser and the maximum fuse clearance time for the simulated faults. In this case, it is verified that the means of the $CTIs$ are above 26 s, reaching cases with mean time intervals of 53 s (CG faults with a resistance of 40 Ω). The shortest CTI obtained (1.6285 s) was for a BG fault with an impedance of 40 Ω at bus 810. The most prolonged CTI (87.2342 s) was for a BC fault at bus 888 with an impedance of 5 Ω.

5.2 *Adaptive adjustment*

In this subsection, the results obtained for the recloser with automatic adjustment of the TD of the delayed characteristic curve will be presented. It should be remembered that the fast characteristic curve has the TD set at 0.05.

Table 10 shows the recloser operating times with automatic adjustment for BG short circuits with a resistance of 40 Ω. Comparing this table with Table 2, it is possible to verify that there was a significant reduction in the recloser operating times considering the delayed characteristic curve. While in Table 2, the times were all greater than 17 s, in this case, the times were all below 24 s. This is interesting because, for faults that do not involve fuses (bus 806, 828, and 860), these will be eliminated (if they are permanent faults) due to the delayed time, which in this case, is faster.

Also, in Table 10, it is possible to observe that the fast operation times are the same as in Table 2, considering that the same adjustments were adopted for this curve. Besides, for the fault at bus 810, the same tripping time was obtained for the delayed characteristic curve, in order to obtain the same TD of the recloser with fixed adjustment. Finally, it is observed that a TD of 0.10 would be sufficient for most cases.

Table 11 shows the $CTIs$ between the recloser and the fuses for the BG fault with a resistance of 40 Ω. It should be noted that the fuse times are the same as those shown in Table 3. In this case, it is possible to observe that all $CTIs$ were above 200 ms. Also, when comparing Table 11 with Table 4, it is possible to verify a significant decrease in the $CTIs$ obtained when considering the recloser delayed operation curve and the maximum fuse clearance time. In this case, a maximum CTI of 3.6387 s is observed, while in the previous case, the highest value obtained was 53.3809 s (Table 4). Finally, it is worth noting that the $CTIs$ obtained, considering the recloser fast operation curve and the minimum fuse time, are the same in both tables, given that there was no change in the actuation times of the devices for these char-

Table 8: Mean and standard deviation of the CTI considering the recloser fast operation and the minimum melting time of the fuse (fixed setting)

Type of fault	Fault resistance (Ω)							
	0.01		5		20		40	
	Mean (s)	Std (s)	Mean (s)	Std (s)	Mean (s)	Std (s)	Mean (s)	Std (s)
AG	0.9046	0.4071	1.1086	0.4599	1.7239	0.7498	3.2876	1.9117
BG	0.6272	0.2343	0.7820	0.2234	1.3102	0.2341	3.0578	2.2792
CG	11.6127	26.6534	0.9370	0.0435	1.4084	0.0819	2.3466	0.2132
AB	1.7773	3.1448	1.0439	1.0453	0.7563	0.0559	1.0662	0.0955
BC	1.6423	2.9624	0.9300	0.9356	0.6708	0.0567	0.9479	0.1024
CA	1.5752	2.7864	0.9732	1.0070	0.6957	0.0594	0.9955	0.1077
ABG	0.8897	1.3476	10.0537	21.4991	0.7033	0.0362	1.2623	0.0939
BCG	0.7780	1.0603	5.5957	11.5105	0.7144	0.0365	1.2806	0.0954
CAG	0.9882	1.4242	0.5177	0.0173	0.8311	0.0374	1.4854	0.0970
ABC	0.8149	1.1504	11.7014	27.4324	0.4717	0.0155	0.5910	0.0227
ABCG	0.7848	1.1135	0.4313	0.0150	0.7187	0.0339	1.3387	0.0913

Table 9: Mean and standard deviation of the CTI considering the recloser delayed operation and the maximum clearance time of the fuse (fixed setting)

Type of fault	Fault resistance (Ω)							
	0.01		5		20		40	
	Mean (s)	Std (s)	Mean (s)	Std (s)	Mean (s)	Std (s)	Mean (s)	Std (s)
AG	32.4546	5.8405	33.0440	5.4182	37.5483	5.3128	42.1197	6.2240
BG	32.2408	10.5236	32.7428	10.3990	38.4706	10.8528	44.5143	16.2386
CG	38.5275	2.9115	39.1303	0.5221	45.1151	0.5125	53.5049	0.5209
AB	29.1509	2.0130	36.3569	16.2877	32.2633	0.3670	36.5650	0.3545
BC	31.3987	2.4725	40.8089	20.7660	35.2600	0.4473	40.3979	0.4493
CA	31.8739	2.7713	39.2890	16.9485	34.9312	0.4334	39.2131	0.4252
ABG	30.6028	6.5311	28.6730	0.3742	34.0385	0.3558	41.2097	0.3478
BCG	28.7467	2.8728	29.2750	0.3851	34.8701	0.3697	42.5272	0.3740
CAG	31.6698	12.0628	27.2622	0.3161	31.7859	0.2856	37.6138	0.2846
ABC	32.6512	17.3129	29.7057	9.8213	27.0897	0.3194	29.4844	0.3156
ABCG	32.9956	17.2755	26.8369	0.3245	32.2339	0.3034	39.3729	0.2849

acteristics.

Table 12 shows the recloser tripping times for an ABC fault with an impedance of 0.01 Ω. Again, it is noted that the recloser operation times, considering the delayed operation, are very small when compared to the times obtained in Table 5. Besides, it is possible to verify that, in this case, a TD of 0.10 would be enough to obtain coordination for the cases presented. Finally, it is interesting to highlight the reduction in the time of delayed tripping for faults that do not involve fuses (bus 806, 828, and 860). A reduction from 30.4871 s to 2.1055 s (short circuit at bus 860) can be crucial to safeguard electrical system equipment.

Table 13 shows the $CTIs$ obtained for the ABC fault with an impedance of 0.01 Ω. Again, it is observed that all $CTIs$ were above the minimum value (200 ms). Furthermore, there is a significant reduction in the CTI considering the recloser delayed time and the maximum fuse clearance time when compared to Table 7. In this case, a maximum CTI of 2.6260 s was obtained, while in Table 7, the shortest CTI was 24.2462 s (considering the recloser delayed time and the maximum fuse clearance time).

Table 14 shows the mean times and standard deviations of the $CTIs$ obtained for the different types and fault resistance, considering the delayed tripping time of the recloser and the maximum fuse clearance time. In this case, it is verified that the mean times are below 4 s, being the shortest mean time of 0.3350 s (AB faults with a resistance of 40 Ω). Considering all applied faults, the shortest CTI obtained was 0.2784 s for a CAG fault with an impedance of 20 Ω. The most significant CTI obtained was 8.6560 s for an AC fault of 0.01 Ω.

When comparing Table 14 with Table 9, it is possible to verify that the mean of the $CTIs$ obtained with the adaptive adjustment is much smaller than those obtained with the fixed adjustment. This results in shorter fault dwell time in the event of a fuse failure. Besides, smaller stan-

Table 10: Tripping times and TDs of the recloser, with adaptive adjustment, for BG faults with resistance of 40 Ω

Fault location	Fast time (s)	Delayed time (s)	TD
806	0.1762	1.2109	0.05
810	0.2486	23.3011	0.75
826	0.4483	5.0466	0.10
828	0.4370	2.5147	0.05
856	0.6775	6.8903	0.10
888	-	-	0.05
890	-	-	0.05
842	0.7629	7.5364	0.10
844	0.7700	7.5909	0.10
846	0.7884	7.7266	0.10
848	0.7911	7.7449	0.10
860	0.7714	3.8386	0.05
862	0.7859	7.7104	0.10
838	0.8093	7.8833	0.10

- Not sensitized

Table 11: CTI between adaptive adjustment recloser and fuse, for BG faults with resistance of 40 Ω

Fault location	CTI between fast time & minimum time (s)	CTI between maximum time & delayed time (s)
810	9.4361	1.6285
826	1.8811	1.8767
856	1.7834	3.5526
842	2.1118	3.6387
844	2.1582	3.6147
846	2.2746	3.5419
848	2.2909	3.5308
862	2.7093	2.8078
838	2.8749	2.6298

Table 12: Tripping times and TDs of the recloser, with adaptive adjustment, for ABC faults with resistance of 0.01 Ω

Fault location	Fast time (s)	Delayed time (s)	TD
806	0.0859	0.4485	0.05
828	0.1970	1.3316	0.05
888	0.3521	2.1231	0.05
890	1.2777	11.1849	0.10
842	0.2732	1.7427	0.05
844	0.2759	1.7540	0.05
846	0.2834	1.7929	0.05
848	0.2845	1.7974	0.05
860	0.3474	2.1055	0.05
862	0.2828	1.7906	0.05

dard deviations of the results are also observed, given that the CTI will always tend to be close to the minimum value (200 ms).

Table 13: CTI between adaptive adjustment recloser and fuse, for ABC faults with resistance of 0.01 Ω

Fault location	CTI between fast time & minimum time (s)	CTI between maximum time & delayed time (s)
888	0.2060	1.4154
890	3.6291	2.6260
842	0.3555	0.9306
844	0.3633	0.9286
846	0.3834	0.9327
848	0.3862	0.9323
862	0.3810	0.9332

Table 15 shows a statistical evaluation of the TDs obtained for the short circuits applied. Note that 50% of the cases, regardless of the type of fault, obtained the minimum TD (0.05). When considering 75% of the cases, AG, BG, ABG, BCG, and CAG faults obtained a TD of up to 0.10. This shows that most of the TDs obtained were low. Finally, note that TDs greater than 0.75 (value set in the fixed adjustment) were obtained only when the fusion times are greater than 100 s. These cases were not considered when determining the TD for the fixed adjustment.

6 Conclusions

The simulation with the automated adjustment has shown a significant reduction in the recloser operation times considering the delayed curve. This is an interesting result since for faults that do not involve fuses can be mitigated more quickly, because the recloser will use the smallest TD. Besides, the use of the proposed method allows the protection system to be better coordinated, given the shorter $CTIs$. Finally, it is also verified that in case of communication failures, the proposed method will not have major negative consequences, resulting in only a loss of selectivity.

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Table 14: Mean and standard deviation of the CTI considering the recloser delayed operation and the maximum clearance time of the fuse (adaptive setting)

Type of fault	Fault resistance (Ω)							
	0.01		5		20		40	
	Mean (s)	Std (s)	Mean (s)	Std (s)	Mean (s)	Std (s)	Mean (s)	Std (s)
AG	1.0747	0.5947	0.9051	0.5925	2.2037	0.8720	1.9131	0.4322
BG	1.0199	0.3518	0.8571	0.1509	0.9383	0.9248	2.9802	0.7438
CG	1.1460	0.3822	0.8974	0.0350	0.5460	0.1073	3.4524	0.3229
AB	1.5067	1.4852	0.9055	0.2945	0.6430	0.0338	0.3350	0.0382
BC	1.7148	1.5188	1.4237	1.0003	0.8834	0.0361	0.6270	0.0406
CA	2.1878	2.6531	1.1984	0.5396	0.8212	0.0419	0.4946	0.0543
ABG	1.5281	1.7338	0.6047	0.0181	2.5343	0.0549	1.8857	0.2620
BCG	1.2056	0.6163	0.7804	0.0154	0.8907	0.9325	2.4599	0.2156
CAG	1.5093	1.6381	0.6482	0.0192	2.0094	0.8670	1.8218	0.2188
ABC	1.2427	0.5889	1.0016	0.1614	0.9152	0.0077	0.8720	0.0179
ABCG	1.2101	0.5067	0.9224	0.0043	0.7762	0.0377	1.8975	1.3084

Table 15: Statistical evaluation of TD obtained by the adaptive adjustment

Type of fault	Min	25th perc.	Median	75th perc.	Max
AG	0.05	0.05	0.05	0.10	1.80
BG	0.05	0.05	0.05	0.10	1.30
CG	0.05	0.05	0.05	0.07	1.15
AB	0.05	0.05	0.05	0.05	0.55
BC	0.05	0.05	0.05	0.05	0.40
CA	0.05	0.05	0.05	0.05	0.35
ABG	0.05	0.05	0.05	0.10	1.70
BCG	0.05	0.05	0.05	0.10	1.55
CAG	0.05	0.05	0.05	0.10	2.15
ABC	0.05	0.05	0.05	0.05	2.05
ABCG	0.05	0.05	0.05	0.05	2.05

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