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Didatic Overcurrent Protection Coordination for the IEEE 34-Node Radial Test Feeder ⋆

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Abstract: The IEEE Test Feeders are used in general for power flow testing methods. However the studies of it can be extended to other applications, as power system protection. This paper proposes an overcurrent protection (OCP) coordination for IEEE 34-Node Radial Test Feeder, based on the protection philosophies commonly used in Brazil, by a practical and didactic methodology. The OCP coordination proposed consist in two reclosers (R), one at substation and other at the middle of the main trunk, and fuses at the laterals. The recloser-recloser, recloser-fuse and fuse-fuse coordinations are presented and discussed. The methodology and the OCP devices used may be extended to others IEEE or real feeders. Moreover, this OCP scheme may be used as a start point to evaluate the impacts of high penetration of distributed energy resources on this feeder.

Keywords: overcurrent protection; power system protection; faults; protection coordination.

1. INTRODUCTION

The first set of open-available distribution test feeders models was released in 1991 by the Test Feeder Working Group (TFWG) (Kersting, 2001; Power & Energy Society (PES), 2018). The IEEE 34-Node Test Feeder (IEEE 34-NTF) belongs to the TFWG models. It has unbalanced loading and it is a very long feeder which requires the application of voltage regulators.

The objective of this work is to propose a didactic overcurrent protection (OCP) scheme for the IEEE 34-NTF, based on the protection philosophies and protection devices commonly used in Brazil, aiming to help professionals and students who does not have much experience in protection studies. This study uses a radial system, due to its predominance in the distribution system, in addition to computational tools commonly used by Brazilian electric power companies.

Moreover, the recloser-recloser coordination for phase and neutral protection curves, recloser-fuse and fuse-fuse coordinations are didactically determined by a practical methodology and using off-the-shelf devices. The data from test feeders Kersting (2001) and IEEE website (Power & Energy Society (PES), 2018) were used to implement the overcurrent protection devices (OCPD) settings, location and coordination studies.

Although some authors like (Funmilayo and Butler-Purry, 2009; Gomez and Morcos, 2005; Butler-Purry and Funmilayo, 2009) have published similar papers, proposing methodologies to make a electric network protection study, it can be observed that recently the works are focused on develop new methodologies to optimize protection, including distributed generation, which is also important (Resende et al., 2019; Shabani and Mazlumi, 2020; Rebizant et al., 2018). The authors of this work, however, observed a need for students and also professionals in the electric field to learn more about the overcurrent protection studies. This initial basic knowledge is crucial for further research in the field of protection to advance.

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2. IEEE 34-NODE RADIAL TEST FEEDER

The IEEE 34-NTF is an actual feeder located in Arizona, United States of America. As shown in Fig. 1, it is composed by a main three-phase trunk, with single-phase laterals (Laterals 1, 2, 3, 4 and 6), three-phase laterals (Laterals 5 and 7) and a three-phase combined with single-phase lateral (Lateral 8). The step-down transformer (XFM-1) feeds the node 888, which operates in 4.16 kV. The reactive power compensation is given in Lateral 7 by two three-phase capacitor banks at nodes 844 (Cap-844) and 848 (Cap-848).

All these components need an OCP to guarantee system reliability and interrupt the current flow when an abnormality, such as a short-circuit, happens.

2.1 Methodology

The OCP study involves determining the type, location, and settings of OCPD for different fault levels. The coordination study will utilize data from equipments datasheet to generate the reclosers and fuses curves. These data were implemented in a Microsoft® Excel® macro which

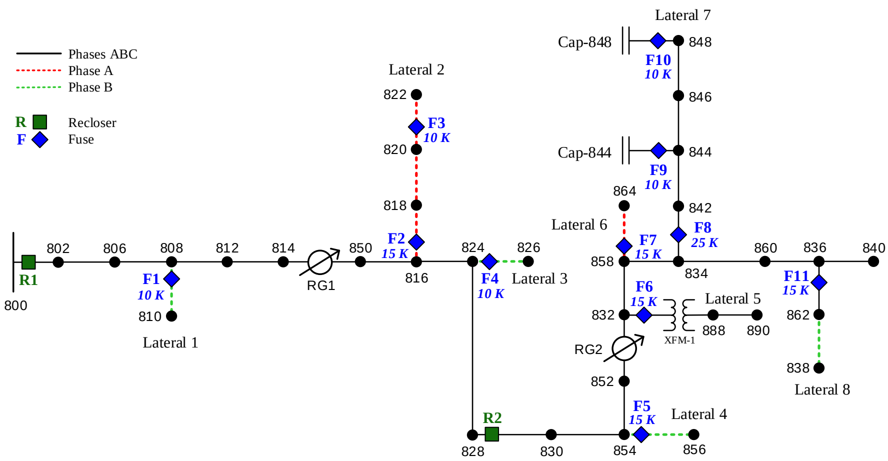

Figure 1. The IEEE 34-Node Radial Test Feeder circuit and the suggested overcurrent protection scheme.

contains data from protection curves and parameters of several manufacturers, used by some Brazilian electricity distribution companies to carry out their protection studies.

All data were entered and extracted from this macro, including the coordination time intervals and the graphs that will be presented in this work.

2.2 Placing OCPD

Due to the feeder extension, it was proposed the use of two reclosers. The recloser 1 (R1) was placed near the substation, and recloser 2 (R2) at the node 828, distant 35.09 km from R1, ensuring an approximate division of loads for each OCPD, as can be seen in Fig. 1.

The fuses (F#) were placed on all lateral branches. Fuses were also used to protect the capacitor banks, Cap-848 and Cap-844, and the step-down transformer (XFM-1). The suggested OCPD location are represented in Fig. 1. The OCPD parameters were determined by steady-state and short-circuit currents from IEEE report data.

The Table 1 presents the load-flow results for maximum load current through each OCPD, from the IEEE report (Kersting, 2001). These values are used to determine the pick-up current of reclosers and the settings of fuses.

Table 1. Maximum Nominal Branch Current

OCPD	**Node**		**Current (A)**
	From	**To**	
R1	800	802	51.56
R2	828	830	37.77
F1	808	810	1.22
F2	816	818	13.02
F3	820	822	10.62
F4	824	826	3.1
F5	854	856	0.31
F6	832	XFM-1	11.7
F7	858	864	0.14
F8	834	842	16.3
F11	836	862	2.09

2.3 Short-circuit Analysis

Differently from Funmilayo et al. (2012), the short-circuit results were obtained directly from Power & Energy Society (PES) TFWG website (Power & Energy Society (PES) (2018)).

The short-circuit results (Kersting (2001)) shows the maximum and minimum fault currents at each node of the IEEE 34-NTF, and it was conducted following the assumptions determined by Kersting and Shirek (2012).

The faults values at the nodes downstream of the OCPD were used to determine the operating times of OCPD during maximum faults and the devices reach. A three line-to-ground (3LG) fault with zero fault impedance was used as the maximum fault for the three-phase lines, while single line-to-ground (SLG) faults with zero fault impedance were used for the single-phase lines.

The minimum fault was took at farthest node downstream of OCPD. For minimum fault, SLG fault with 20 Ω resistance was used for all laterals. For reclosers coordination, a double-line fault, with 20 Ω resistance, was used.

To provide the coordination of OCPD, the data utilized contains the minimum and the maximum steady-state fault currents from laterals and main trunk, maximum nominal current and time-current curve (TCC) database of OCPD.

The maximum fault current at the node 800, for R1, is 627.3 A and at the node 828, for R2, 292.8 A. The minimum fault current observed at R1 for the minimum fault on laterals downstream from it until R2, for all nodes, is 136 A. The smaller value of the short-circuit observed at R2 for the minimum faults on laterals downstream from it is 94 A (Power & Energy Society (PES) (2018)).

3. COORDINATION STUDIES

With the proposed OCP for IEEE 34-NTF, some possible fault scenarios can be analysed with respect to the temporary and permanent fault conditions. The OCPD operation and coordination (recloser-recloser, recloser-fuse, fuse-fuse) during each case will be discussed.

In a protection study, the OCPD curves must coordenate with the upstream and downstream devices. This guarantee that all the OCPD will operate in their correct manner isolating only the faulty part, without harming the others.

3.1 Fault on Main Trunk – Recloser-recloser Coordination

For a fault in main trunk, only the reclosers must operate. This means that, for a fault between nodes 800 and 828, only R1 must operate. However, if the fault occur downstream the node 828, R2 must operate first and only if the fault is not eliminated by it, R1 must open.

So, to guarantee the order of the actuation and the reliability, it must exists a safety time interval between the protection curves of these devices. Usually, the relay manufacturers guarantee that values between 200 ms and 500 ms are enough to ensure OCPD coordination (Kindermann (2005)).

To determine the settings for phase and neutral curves from reclosers, it is necessary to know the load current through it (Table 1). This parameter is used to choose the pick-up current, i.e., the minimum current that the device starts to operate. The pick-up current must be higher than the load current. If this is not, the OCPD may operate for load currents, which is undesired.

The neutral pick-up is always lower than the phase. The lower it is, means that the circuit is less unbalanced. Adjusting the neutral pick-up at reduced values increases the sensitivity of the device, which is useful to detect high impedance faults, for example.

To ensure the reach of the OCPD, i.e., ability to identify faults until the end of its protection zone, the lower short-circuit value at the end of the line must be higher than the device pick-up current. This is necessary because, if the short-circuit value is lower than the pick-up, the OCPD will never operate for a fault at this point. For this study, the pick-up currents were set to values smaller than the minimum fault currents presented in section 2.3, and greater than load currents presented in Tabel 1, as can be seen in Table 2.

Table 2. Reclosers Settings and Time Interval

OCPD / Parameters		**1st Trip Operation**		**2nd and 3rd Trip Operation**	
		Phase	**Neutral**	**Phase**	**Neutral**
R1	Pick-up	80 A	20 A	80 A	20 A
	Curve	VI	VI	VI	VI
	Time Dial	0.50	1.00	0.50	1.00
R2	Pick-up	50 A	15 A	50 A	15 A
	Curve	EI	EI	VI	VI
	Time Dial	0.01	0.25	0.60	0.90
Time Interval (ms)		-	-	-872	-427

According to the recloser type and manufacturer, it is possible to choose the type of coordination curve. The most commonly used curves are the International Electrotechnical Commission (IEC) ones: Inverse (I), Very Inverse (VI) and Extremely Inverse (EI). Each one has a characteristic that makes it more appropriate for a specific situations. The Time Dial (TD) is a value assigned to the curve that allows it to be moved up or down. So, the recloser protection curve can be positioned by varying the curve type, the TD and the pick-up current to ensure the correct coordination.

The protection studies depend on the professional knowledge, your experience and the protection philosophies adopted. The R2 was setted up considering an instantaneous first trip operation, for fuse-save philosophy, explained below, and two delayed trips. All the trips operation of R1 are delayed. This configuration was chose due to the fact that all three-phase loads are located downstream R2, so, using a fuse-save philosophy in this recloser, for the first trip, minimize customers interruption. No fast trip curves was setted up in R1 to avoid the entire feeder from being disconnected during a fault, even if it is temporary.

In Fig. 2 is shown the protection study. An important point, highlighted in the graphic by the vertical bars, is the maximum short-circuit value. The phase curve must be coordinate for all currents below this three-phase short-circuit value and the neutral must be coordinate for all values below single-phase maximum short-circuit.

The difference between the delayed and the fast curves are shown in Fig. 3. It is important to note that in R2 fast curve configuration there is an overlap of the phase and neutral. Therefore, the protection curve of this device, in fact, is the composition of the curves, as Fig. 3.

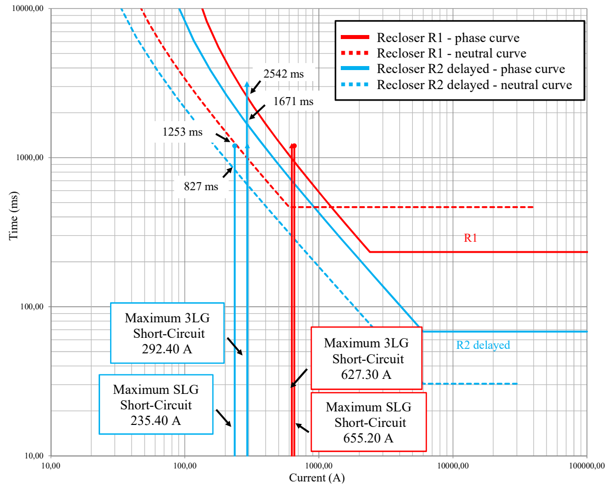

Figure 2. Coordination curves between R1 and R2 delayed.

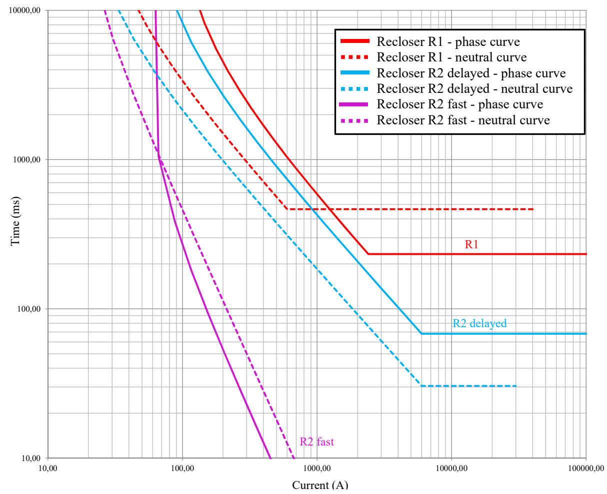

Figure 3. Coordination curves between R1, R2 delayed, and R2 fast.

3.2 Fault on Laterals

If a fault occurs on a lateral , depending on its location, it will require a recloser-fuse or a fuse-fuse coordination.

Recloser-fuse Coordination Basically there are two ways to coordinate the reclosers and fuses: fuse-blow and fuse-save. When the levels of energy quality are a priority, it is usual that the fuse operates first ensuring that a greater share of consumers remain connected. The fuse-blow eliminates all permanent and temporary faults. As it is known that most of the faults are temporary, uses this protection scheme could be efficient (G. Kindermann, 1997; Mamede Filho and Mamede, 2011).

The fuse-save philosophy minimizes customer interruption time by opening the recloser faster than it takes to melt the fuse. This is a good strategy for the feeders located in difficult maintenance areas. The disadvantage, however, is that a larger number of consumers remains momentarily out of power, which can impact on energy quality index.

This work chose to use the fuse-save coordination for temporary faults on laterals downstream R2. A fast curve was setted up for the first trip of R2, shown in Fig. 3. Thus, if the fault is temporary, it will be eliminated by the recloser and it will not be necessary change a fuse link.

The protection study highlighting the fuse-save philosophy is represented in Fig. 4. It is possible to observe that for short-circuit values less than or equal to approximately 200 A, which corresponds to the most of the short-circuit values at the nodes where there are fuses, R2 will operate first to 15 K and 25 K fuses. Moreover, R2 fast curve does not operate faster than the 10 K fuse. So, this curve was adjusted aiming to meet all the protection criteria of the feeder elements.

If the fault remains over the R2 fast trip, fuses must clear the fault before the second or third operation of R2 delayed curve (Table 2), as can be seen in Fig. 5. If the fault is not eliminated by the fuses, the recloser-recloser coordination actuates.

For faults on the laterals downstream R1 and upstream R2, the fuse-blow philosophy was adopted, as shown in Fig. 5, neglecting the R2 delayed curve. The fuses operates prior to R1 curves isolating the laterals, avoiding the entire feeder from being disconnected. If the fault on this laterals remains, R1 will open disconnecting the entire feeder.

Fuse-fuse coordination Usually, the K fuse links are the most used in distribution grids to protect branches due to its fast operation (Celesc, 2014). To correctly chose it, it is necessary to know the load current at the node where the fuse is installed. Additionally, the fuse curves must coordinate with the reclosers upstream of it. The fuse supports a nominal current up to 150% of the value measured at the installation point (Eletrobrás, 1982). The device must be able to conduct this current indefinitely, without the temperature rises exceed the specified values (Celesc, 2014).

So, as the fuses was chosen based on the load current, it was a protection project choice to use the links, as shown in Fig. 1 In this way it was possible to maintain coordination between the fuse links in sequence.

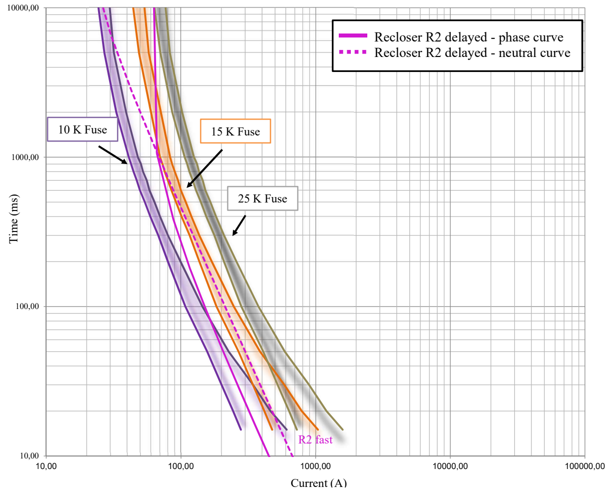

Figure 4. Coordination curves between R2 fast and fuses.

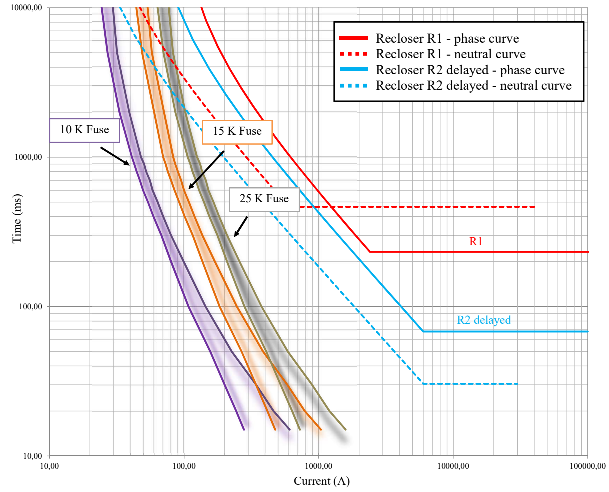

Figure 5. Coordination curves between R1, R2 delayed and fuses.

3.3 Fault with Step-down Transformer: Lateral 5

The fuse link must operate for the faults on the primary or secondary side of the transformer, eliminating the effects of failure in the primary grid and it should support, without melt, the same overload current that the transformer is able to (IEEE, 2000).

When subjected to a current of 250% to 300% of the rated current of the transformer, the fuse link may melt within 17 seconds. The fuse also needs to withstand transient magnetizing current for 0.1 seconds. This current is estimated at 8 to 12 times of nominal current of the power transformers up to 2000 kVA (Eletrobrás, 1982). As XFM-1 is a 500 kVA distribution transformer, the fuse links used to protect are normally H or K type, depending on the power rating of the transformer. The H type are high-surge with slow-action for current surges, e.g., the transient transformer magnetizing current. They are used only for small nominal currents. So, it can protect the transformers of small powers (up to 75 kVA) and the small capacitor banks (Cemig, 2017).

The Eq. (1) is used to calculate nominal current at primary side of XFM-1. According to Mamede Filho and Mamede

Table 3. Recloser-Fuse Coordination Time

R	**Fuse**		**Short-circuit (A)**		**Recloser Delayed Operation Time (ms)**	**Fast Operation Time (ms)**	**Fuse Operation Time (ms)**	**Time Interval ($t_{\text{fuse-tR2-fast}}$) (ms)**	**Time Interval ($t_{\text{fuse-trecloser-delay}}$) (ms)**
R1	F1	10 K	Min	298	971	none	37	none	-934
			Max	474.6	594	none	19	none	-575
	F2	15 K	Min	135.3	2342	none	300	none	-2042
			Max	313.9	919	none	70	none	-849
	F4	10 K	Min	148	1585	none	65	none	-1520
			Max	258.9	984	none	37	none	-947
R2	F5	15 K	Min	148	1370	103	280	150	-1090
			Max	258.9	1465	118	300	182	-1165
	F7	15 K	Min	139.4	1465	118	290	172	-1175
			Max	208.9	940	49	160	111	-780
	F8	25 K	Min	133.6	1537	130	850	720	-687
			Max	203.4	967	51	320	269	-647
	F9	10 K	Min	136	none	125	120	-5	none
			Max	201.3	none	53	60	7	none
	F10	10 K	Min	133.6	none	130	120	-10	none
			Max	198.1	none	54	60	6	none
	F11	15 K	Min	131.4	1566	135	330	195	-1236
			Max	199.1	990	54	180	126	-810

(2011), the fuse link necessary to provide proper XFM-1 protection, F6 in Fig. 1, is a 15 K fuse.

$$I_{\text{nominal}} = \frac{S}{\sqrt{3}\ V_{\text{nominal}}} = \frac{500}{\sqrt{3}\ 24.9} = 11.6\ A \qquad (1)$$

3.4 Fault with Reactive Compensation: Lateral 7

To protect the capacitor banks, it is also necessary a fuse in a group-fuse philosophy (Funmilayo et al., 2012). The procedure for correctly dimensioning the device is determine the capacitor banks nominal current and then multiply this current by 1.25 for ungrounded banks and 1.35 for grounded banks, at first. After this, it is necessary to divide the current value obtained by 1.5 to determine the minimum fuse link. Lastly, it is necessary to check if the fuse link coordinates with the tank rupture curve in the safe zone and if the chosen fuse supports the higher inrush current (Eletrobrás, 1982).

The nominal current of the capacitor banks were calculated by (2) using the capacitor banks data: the total reactive power (Q_{total}) are 300 kVAr for Cap-844 and 450 kVAr for Cap-848.

$$I_{C_{\text{bank}}} = \frac{Q_{\text{total}}}{\sqrt{3}\ V_{\text{nominal}}} \qquad (2)$$

As that the voltage of the feeder is 24.9 kV, the nominal current for Cap-844 is 6.96 A and for Cap-484, 10.43 A. Both capacitor banks are grounded, so these values need to be multiplied by 1.35 resulting in 9.40 A and 14.10 A respectively.

It is known that if a capacitor unit fails, at steady-state frequency, its protection fuse must operate first than other protective devices (Funmilayo et al., 2012). So, the R2 fast curve was chosen in order to allow that F9 and F10 operate prior to it, following fuse-blow philosophy. Then, as the K fuse are recommended to protected capacitor banks, the chosen fuse links for the both capacitor banks are 10 K.

4. RESULTS AND DISCUSSION

For a recloser-fuse coordination, the results were computed by comparing the recloser's fast and delayed clear time to the fuses's maximum melt time. For a fuse-fuse coordination, the results were computed by comparing the fuse's maximum melt time to the minimum melt time. For a recloser-recloser coordination, the results were computed by comparing the R1 clear time to the R2 delayed clear time.

The coordination times between the reclosers and fuses are highlighted in Table 3. The negative values represents that fuses operate prior to the R1 or R2 respective curves.

For R1, respecting the fuse-blow philosophy, fuses operates first than R1 curve, and the coordination time interval between fuses (F1, F2 and F4) exceeds 34 cycles or more during maximum faults. For the minimum faults, in average, the time interval is added of 22 cycles. For R2, the fast curve operates first than F5, F7, F8 and F11, respecting the fuse-save philosophy. The minimum coordination time interval exceeds 6 cycles. Fuses operate prior to R2 delayed curve, with a coordination time interval that exceeds 38 cycles.

The fuses F9 and F10, which represent the capacitor banks fuses, must operate first than R2 fast curve. For this case, the worst coordination time was analysed: the maximum melt fuse operation. The fuse F9 operates 0.42 cycles slower than R2 fast curve and F10 operates 0.36 cycles slower, for the minimum interval. However, it is important to note that this value may be lower considering the fact that the fuse links have an operating range and may melt before the maximum melt time.

The coordination times between the fuses on laterals with more than one fuse protection are highlighted in Table 4. The negative time interval values represents that downstream fuse operate prior than upstream fuse. On Lateral 2, F3 operates 4.3 cycles before F2, for the worst case, the maximum short-circuit current. On Lateral 7, F9 and F10 operates, in average, 9.7 cycles before F8, for the worst case.

Table 4. Fuse-Fuse Coordination Time

Fuse		Minimum Short-circuit (A)	Device Operation Time (ms)		Total Time Interval (ms)	Maximum Short-circuit (A)	Device Operation Time (ms)		Total Time Interval (ms)
F2	15 K	135.3	$t_{min\text{-}melt}$	200	-85	157.3	$t_{min\text{-}melt}$	160	-73
F3	10 K		$t_{max\text{-}melt}$	115			$t_{max\text{-}melt}$	87	
F8	25 K	136	$t_{min\text{-}melt}$	550	-440	201.3	$t_{min\text{-}melt}$	220	-160
F9	10 K		$t_{max\text{-}melt}$	110			$t_{max\text{-}melt}$	60	
F8	25 K	133.6	$t_{min\text{-}melt}$	560	-440	197.5	$t_{min\text{-}melt}$	230	-165
F10	10 K		$t_{max\text{-}melt}$	120			$t_{max\text{-}melt}$	65	

The coordination times between the reclosers are shown in Table 5. The negative time interval values represents that the R2 delayed curve operate prior to the R1 curve for the faults downstream of the R2 location. For the maximum SLG fault, the R2 delayed operate 25.5 cycles before R1, and for the maximum 3LG fault, R2 delayed operate 52.2 cycles before R1, respecting the safe coordination time interval (Kindermann, 2005). The results shows that the practical methodology provide an adequate coordination range between the cases analysed, and respecting the protection philosophy adopted.

Table 5. Recloser-Recloser Coordination Time

Short-circuit	Time Operation (ms)		Total Time Interval (ms)
	R1	R2 Delayed	($t_{R2\text{-}delayed}$ - t_{R1})
Maximum SLG	1253	827	-426
Maximum 3LG	2542	1671	-871

This protection scheme may be used to assess the impacts of a high integration of distributed energy resources, such as small-scale photovoltaic generators, e.g., on the safety time interval between the OCPD, and the methodology can be used to change the settings of OCPD on this situation.

5. CONCLUSION

This paper provides an adequate coordination study allowing a comprehension of how the OCPD are parametrized and how it can be done, in most of cases, in Brazilian energy utility companies. The methodology covered the main coordination issues of a distribution feeder: recloser-recloser coordination; fuse-fuse coordination, including capacitor banks and power transformer protection; as also the recloser-fuse coordination, including fuse-save and fuse-blow philosophies. This study can be used to evaluate the impacts of the integration of distributed energy resources on short-circuit currents and load currents. Moreover, the methodology can be used to redo the settings of OCPD of the proposed scheme in this new scenario, proposing an alternative solution.

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