Reclosers Modeling for Temporal Simulation of Distribution Networks in Simulink/Matlab®

R. L. A. Pereira, R. C. D. Lima, H. D. M. Braz, N. S. D. Brito, P. H. F. Monteiro, and J. P. N. Amoah

***Abstract*—Over the past few years, Brazil's increasing dependence on electricity has caused a continuous growth in demand and, therefore, the need to guarantee long-term energy supply to custumers. Hence, studying the devices that are responsible ensuring this continuity is critical since the improper operation of this equipment can reduce the reliability of the electrical energy distribution system, therefore requiring detailed study that incorporates simulations, modeling, and analysis of response capacity in the face of real loads. Simulink/Matlab® is one of the most widely used software programs in academia. However, it does not have readymade templates for protection system equipment such as relays, fuses, and reclosers. Herein, the aim is to model the digital recloser using the S-function block of Simulink/Matlab®. The proposed model for the recloser follows the configurations required by Brazilian electricity distribution companies, i.e. four operations divided into fast and slow, the latter one being responsible for permanently opening the section of the system on fault. To validate the modeled device, the IEEE 34-bar system was used, in which several operational cases were considered. The results obtained show that the proposed digital recloser model performed successfully proved to be a promising proposal for protection studies of power distribution systems.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/8590

***Index Terms*—protection, digital recloser, electricity distribution systems.**

I. Introduction

The power supply is one of the biggest concerns for electric distribution companies because there are penalties in the event of faults. These penalties were created due to society's increasing dependence on electricity. Among the concessionaires' efforts to guarantee a continuous and high-quality power supply, the search for continuous improvement of protection schemes stands out. In Brazil, the National Electric Energy Agency (ANEEL) is the entity responsible for ensuring the quality of the services provided by the power concessionaires. To accomplish this, ANEEL monitors several parameters, especially the Interruption Service Indicators per Consumer Unit (DEC) and Equivalent Interruption Frequency per Consumer (FEC) [1].

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To provide a proper supply of electricity, as well as to safeguard people and equipment, the Electric Power System has a protection system, which can be defined as a set of equipment and devices installed in the system to protect against unusual operating conditions in system components [2]. When it comes to the traditional Electrical Distribution System (EDS), the protection system is mainly composed of overcurrent relays located on the feeder branch, reclosers and switch-disconnectors along the feeder, sectionalizeres along the feeder and fuses to protect the lateral branches, which must be installed and set up to act in a coordinated way, as illustrated in Fig. 1 [3].

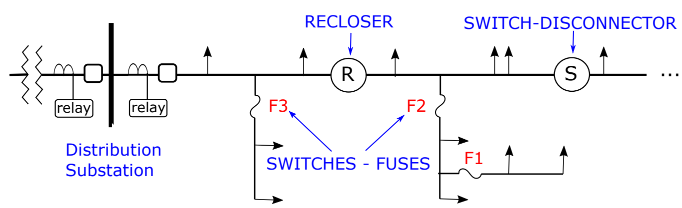

Fig. 1. Typical placement of protection devices.

Examining specialized literature has shown that one of the usual problems in the field of EDS protection is the choice of optimal equipment settings, which explains the detailed studies conducted using a traditional line of research. In this context, this paper is focused on the development of a simulation model for reclosers, which can act in the event of both temporary and permanent faults, mitigating undesirable operations and limiting the affected area, which directly interferes with the measurement of quality indicators.Which resulted in several studies published in the expert literature such as in [4], [5] e [6], which were pioneers in the protection equipment mathematical modeling as relays, fuses and reclosers. Similarly, [7], [8] and [9], which studied the optimum placement of reclosers in the EDS, using mathematical methods to determine their optimum position in the network and minimize the consumers interruption time. In addition, [10], [11] and [12], carried out in-depth studies into the coordination of reclosers with other protection equipment, such as relays and disconnectors, seeking to guarantee the reliability and safety of the electrical system.

Several software programs ara available in the state of the art to conduct studies in the field of Electrical Engineering, one of the most commonly used in Matlab®, undoubtedly. Simulink is the most used module, since it offers a flexible and versatile platform for modeling and simulating of various systems providing the creation of customized models and integration with various tools and libraries. In addition, the software allows integration with hardware-in-the-loop (HIL) tools for real-time simulation [13].

Although Simulink/Matlab® is a powerful tool for simulating electrical systems, it as a downside: the absence of models of equipment that make up the protection system such as relays, reclosers and fuses. To overcome this shortcoming, this paper suggests the computer implementation of a digital recloser in Simulink/Matlab® using the S-function block, so that the modeled system operates similarly to the real EDS different fault scenarios.

The paper has been organized into five sections, including this introductory one. In sections II and III, the fundamentals of recloser operation and modeling are presented, in section IV, the results obtained are presented and discussed. Finally, the conclusions of the work are presented in section V.

II. Recloser Fundamentals

According to [14] - [15] around 84% of faults in overhead networks are of a transient nature, caused by lightning surge or unintentional contact between conductors or other network elements. In order to minimize the recovery time, distributors choose to insert reclosers at strategic points in the network. According to [16], automatic reclosers are overcurrent protection devices capable of interrupting the system's electrical current in a repetitive and coordinated manner, by opening and closing. Their greatest applicability is in the EDS to protect the system from transient faults, not only the faults directly connected to it, but also in the networks protected by fuses downstream to the recloser. The recloser's main feature is its ability to "trip" itself, i.e., when sensed, it sends a signal to the switchgear, which opens the main contacts. After a given predetermined period, the sensor automatically sends another signal to the switchgear, ordering it to close [17].

Brazilian electricity distribution companies, choose to set the recloser with up to three actions, the first two with a shorter interruption than the third one [18]. However, full tripping is only performed in the event of the recloser detecting that after three outages, the EDS remains short-circuited. Reclosers have two groups of curves known as slow and fast. The slow characteristic curves are designed to allow the fuses to trip downstream before the reclose lockout operation; while fast curves act to eliminate transient faults before the recloser's before the fuses operate downstream of the recloser [11], as shown in the coordination in Fig. 2.

Reclosers usually have multiple characteristic curves, some of which are standardized by the IEC and IEEE, and others are developed by the manufacturers themselves [19] - [20]. Based on the state of the art, this research article adopted the IEC Normally Inverse curve, which is mathematically represented by Eq. 1;

$$T_{\text{op}} = \text{TMS}\left(\frac{A}{\left(\frac{I_{cc}}{I_p}\right)^p - 1}\right). \qquad (1)$$

In which, T_{op} is the recloser operating time; TMS is the time multiplier; I_{p} pickup current; I_{cc} the short-circuit current

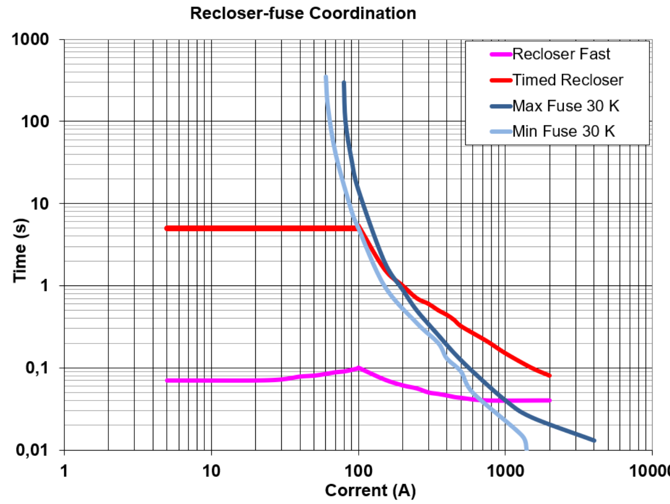

Fig. 2. Coordination between fuse and recloser.

identified in the transformer's secondary; and A and p are the constants that define the recloser operating characteristic curve.

III. Recloser Modeling

State-of-the-art analysis and theSimulink/Matlab® library, presented a gap in models suitable for simulating reclosers. Based on this defect, it was decided to develop it. The S-function level 2 language was used to develop a custom Simulink block in the C and C++ programming languages to define the behavior of the block. Enabling it to be loaded and automatically executed in Matlab®, allowing the integration of customized functionalities into the simulation environment.

The digital recloser modeled in this work has an architecture based on a chain of switches, with two distinct stages. The first one is the opening time, which is defined by Eq. 1, and the second one is the closing time, which can be adapted by the user according to individual requirements of the sections to be protected or the operational features of the distribution system.

As shown in Fig. 3, the device studied has four operations, divided into two intervals of fast operation and two intervals of slow operation, with a reclosing time of 0.5 s between operations [18] - [14]. In other words, in the event of a permanent fault, the recloser will act as system protection, carrying out four predefined operations with the last one responsible for permanently opening the section under its protection, isolating the fault.

Mathematically, recloser operation consists of the sum of opening and reclosing times, which means that the total recloser operating time is expressed by the sum of the recloser's first trip time, interruption time and operating time, as calculated in Eq. 2.

$$\text{T}_{\text{recloser}} = T_O + \sum_{i \in \alpha} T_R(i). \qquad (2)$$

Where T_O is the time of the first trip; $T_R(i)$ is the recloser time; and α is the pair of of interruption and operation times.

This formulation resembles the real reclosers used by utilities in the EDS, respecting the system coordination and selectivity criteria, by parameterizing the modeled equipment.

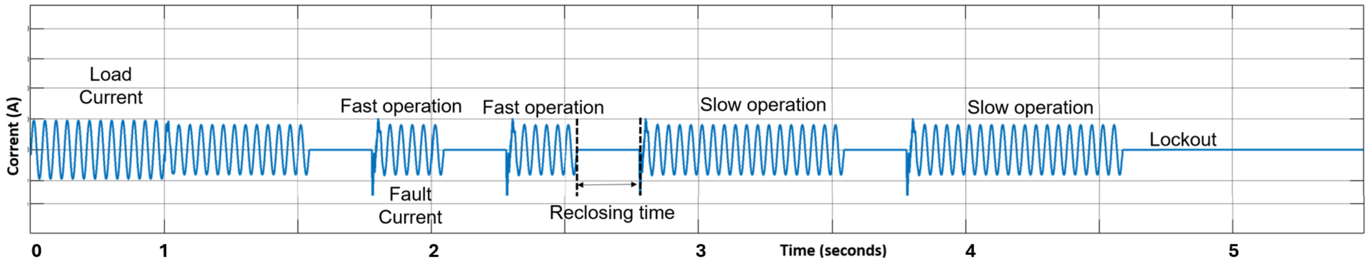

Fig. 3. Typical sequence of operations.

A. Recloser Design

The development of the digital recloser in this work, is based on a strategic combination of available blocks in Simulink and the "S-Function" block. This setup led to the programming of specific functions that were unavailable in the software, following the basic structure of a protection device, as shown in the diagram in Fig. 4.

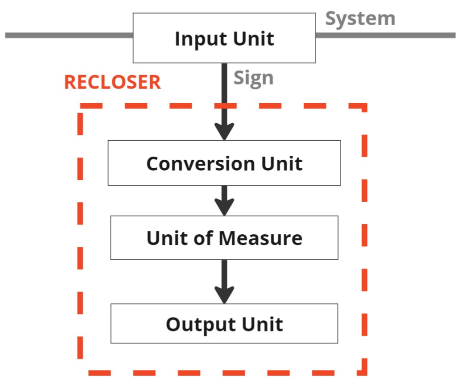

Fig. 4. Basic diagram of the recloser's operation.

The modeling of the recloser focused on the steps following the analog data acquisition by the input unit. In other words, the model simulates the recloser's behavior based on data that has already been collected, deliberately neglecting the modeling acquisition stage. This strategic approach aims to optimize the modeling process by focusing on the functionalities of the recloser.

Fig. 5 presents a detailed diagram of the internal architecture of the modeled recloser. This architecture is composed of several interconnected blocks, each of which is responsible for a specific and critical function for the overall functioning of the system [2] - [21].

*1) **Signal Conversion Unit**:* plays a fundamental role in in preparing the signals coming from the current and potential transformers to be used by the protection system. Its main function is converting and modulating these signals, adapting them to the appropriate level and format for recloser operation [22]. To perform this essential task, the following blocks were modeled:

- **Demux:** responsible for outputting the separate signals by extracting the components of an input vector signal.

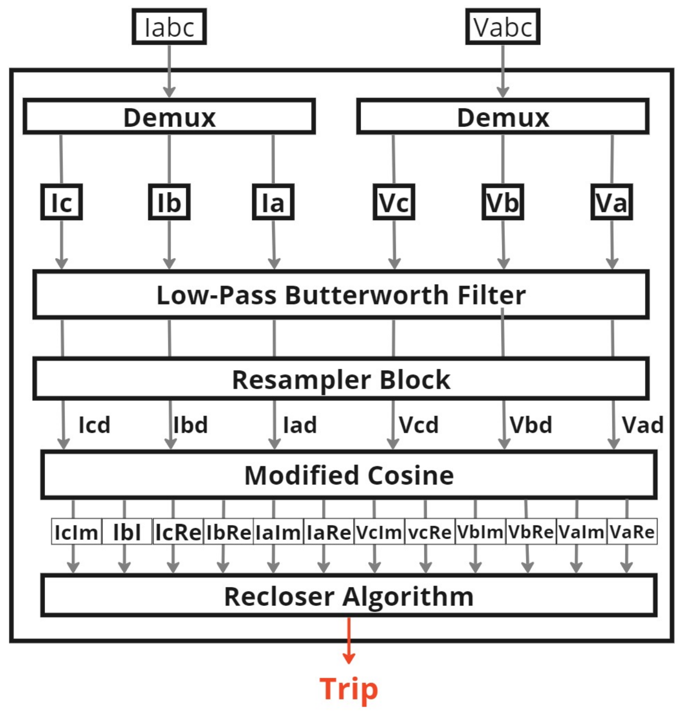

Fig. 5. Digital recloser modeling.

- **Low-pass Butterworth Filter:** responsible for filtering out the high-frequency components according to the Nyquist Theorem. A Butterworth low-pass filter was used due to its usefulness in studies involving the protection system [2].
- **Resampler Block:** responsible for converting analog signals into digital format, with 16 samples per cycle, that is, 960 Hz, which ensures a compromise between processing speed and precision.

*2) **Measurement Unit**:* its main function is to compare the characteristics of the signals received from the signal conversion unit with values that have been previously stored in it and taken as an operating reference [22]. In this context, the following block was modeled:

- **Modified Cosine:** responsible for estimating the voltage and current phasors, which will later be used by the recloser algorithm. The block was programmed via S-function, given its efficiency and low computational effort [2].

*3) **Output Unit**:* the main function is to activate the switching elements, such as secondary contacts or semiconductor switches, to carry out the reclosing maneuvers. In this instance, it was decided to model a block inspired by the recloser's opening and closing behavior.

- **Recloser Algorithm:** the purpose of this block is to emulate the behavior of the recloser, taking the voltage and current values in phasor format as input and the trip signal as output the trip signal, which is responsible for opening and closing of the system.

B. Recloser Algorithm

The recloser was modeled according to the classic architecture. Four blocks were modeled to represent reach reclosing operation, as described in pseudocode 1, with the last trip being responsible for permanently opening and eliminating the fault section in the event of permanent faults. This setup was preferred since it is the one most commonly used by electric utilities [18].

Algorithm 1 Digital Recloser

```
Require: Initial recloser status: OFF
Require: Max. number of reclosures: Num_Max_Reclosure
Require: Reclosing time: Reclosing_time
Require: Fault type: Fault_Type
Initialization:
status_Recloser ← OFF
mun_trigger ← 0
Main Loop:
while (network_State ≠ NORMAL) do
    Reclosing Control:
    if (Fault_Type ≠ PEMANENT_FAULT) then
        if (mun_trigger < Max_Num_Reclosing) then
            Reclosing Attempt:
            status_Recloser ← RECLOSING
            mun_trigger ← mun_trigger + 1
        else
            Permanent Fault:
            status_Recloser ← PERMANENTLY_OPEN
        end if
    else
        Permanent Fault:
        status_Recloser ← PERMANENTLY_OPEN
    end if
    Waiting between reconnection attempts:
    if (status_Recloser = RECLOSING) then
        wait(reclosing_time)
    end if
    Network update status:
    network_State = network_State
end while
Reclosing completed:
status_Recloser ← ON
```

The internal structure of the modeled digital recloser is depicted in Fig. 6. This structure can be understood as a sequence of programmable blocks that execute sequentially. Each block is triggered only after the successful operation of the preceding block, except for Block 01. Block 01 continuously monitors the system voltage and current values to detect the presence of a fault. Recloser operation can be further categorized into two distinct stages:

1) In the Event of a Permanent Fault: block 01 will identify the fault and carry out the first switch opening and closing operation. After the preset closing time is chosen by the user, the enabling signal is sent to block 02. Block 02 checks the voltage and current values of the phases at that instant of time, determining whether the fault has been cleared. If the fault persists, block 02 triggers counter 02 and activates block 03. Block 03 carries out the same signal monitoring procedures, acting for the third time with a longer time than the previous ones (slow operation). Finally, block 04 will be sensitized, identifying the fault and the circuit will be permanently opened.

2) In the Event of a Transient Fault: the processing of the modeled recloser in the event of a transient fault follows the same logic as for a permanent fault, as previously described. Nevertheless, if the fault is extinguished during the intervals between reclosing operations, the device will reset its counters and restore power to the EDS, according to the real reclosers' specifications.

IV. RESULTS ANALYSIS

To assess the behavior of the modeled recloser, the IEEE 34-Node Test Feeder was chosen, as shown in Fig. 7, due to its extensive use by the scientific community for studies related to EDS. This system has a 24.6 kV primary feeder and is qualified for being very long and "lightly" loaded [2] - [23]- [24]. It has shunt capacitors with constant power, current and impedance loads, unbalanced loads [23]. For research purposes, the use of voltage regulators was not considered.

For the purpose of assessing the modeled devices' performance, it was decided to analyze six distinct scenarios, three of which were temporary short circuits and three permanent short circuits, with similar characteristics to the faults endured by traditional EDS. In this context, it is expected that the modeled equipment will perform similarly to a real recloser, once they must operate regardless of the short circuit.

TABLE I
ANALYZED SCENARIOS

Recloser 01			Recloser 02		
Phases	**Bars**	**Fault Type**	**Phases**	**Bars**	**Fault Type**
AG	830-854	Temporary	AB	846-844	Temporary
ABCG	832-858	Temporary	BG	860-836	Permanent
ACG	854-852	Permanent	ABC	842-844	Permanent

A. Recloser 01 Analysis

Aiming to analyze the performance of recloser 01, three faults were simulated on the distribution lines, as detailed in subsections IV-A1, IV-A2, and IV-A3, respectively.

1) Scenario 1 - AG Fault: Given that one of the main functions of the recloser is to restore power to the EDS in the event of a temporary fault, this study analyzed the behavior of the recloser for a short-duration single-phase fault at the beginning of the section between busbars 830-854, with a low resistance of 0.001 Ω. The fault started at time 0.2 s and lasted

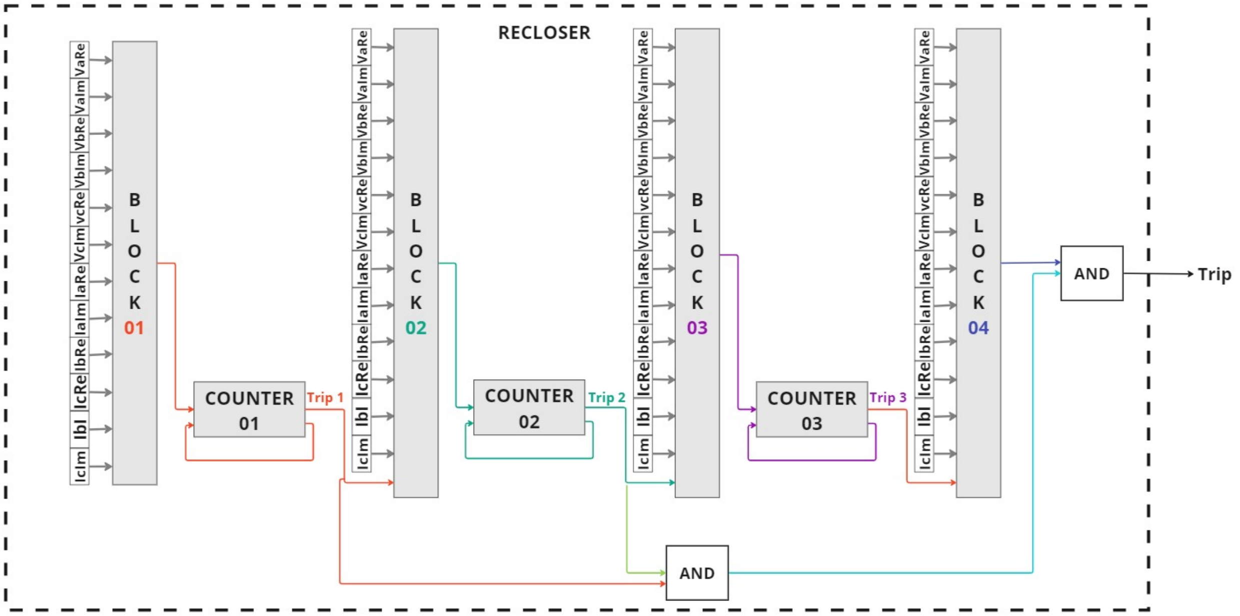

Fig. 6. Digital recloser block (internally).

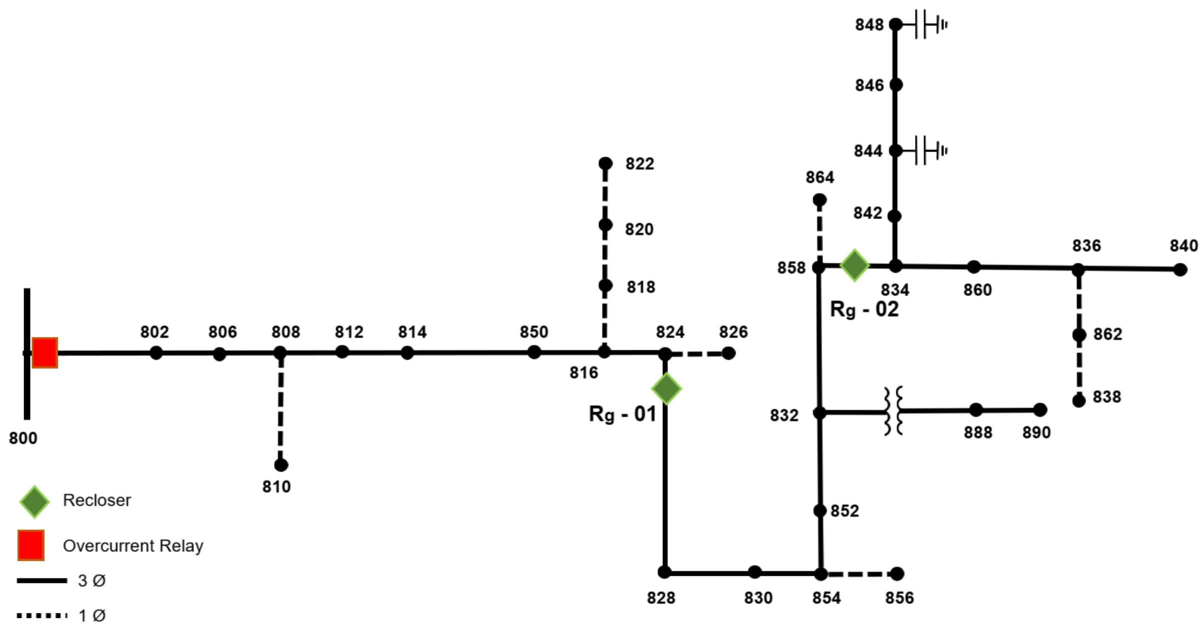

Fig. 7. IEEE 34-bar system.

2.8 s, sensitizing recloser 01 upstream of the fault. The short-circuit current detected by the equipment was approximately 230 A during the fault period.

Fig. 8 illustrates the recloser 01 tripping behavior. The three reclosing attempts were successful, with times of 0.32 s, 1.16 s and 1.99 s after the start of the fault. Given the transient nature of the fault, recloser 01 was able to isolate it and restore the power supply with no need to permanently trip the device.

2) Scenario 2 - ABCG Fault: A three-phase ground fault with a duration of 0.8 s was applied at the end of the section between busbars 832 - 858 with a fault resistance of 0.001 Ω.

As shown in Fig. 9, recloser 01 operated as planned during the three-phase ground fault. A single fast trip was recorded at 0.41 s after fault detection, with a short-circuit current of current of approximately 239 A. The total time, calculated using Eq. 2, was of 1.1 s. This value is in line with the time observed in the dynamic response analysis shown in Fig. 9, which illustrates the interval between detecting the fault and restoring the power supply.

3) Scenario 3 - ACG Fault: In the present study, a permanent ABT type fault was simulated at 0.2 s, at the start of the section between busbars 854 - 852, with a fault resistance of 0,001 Ω. As expected, recloser 01 tripped four times, at intervals of 0.65 s, 2.28 s, 3.92 s and 5.45 s after the fault started, under a fault current of around 254 A. The last trip of

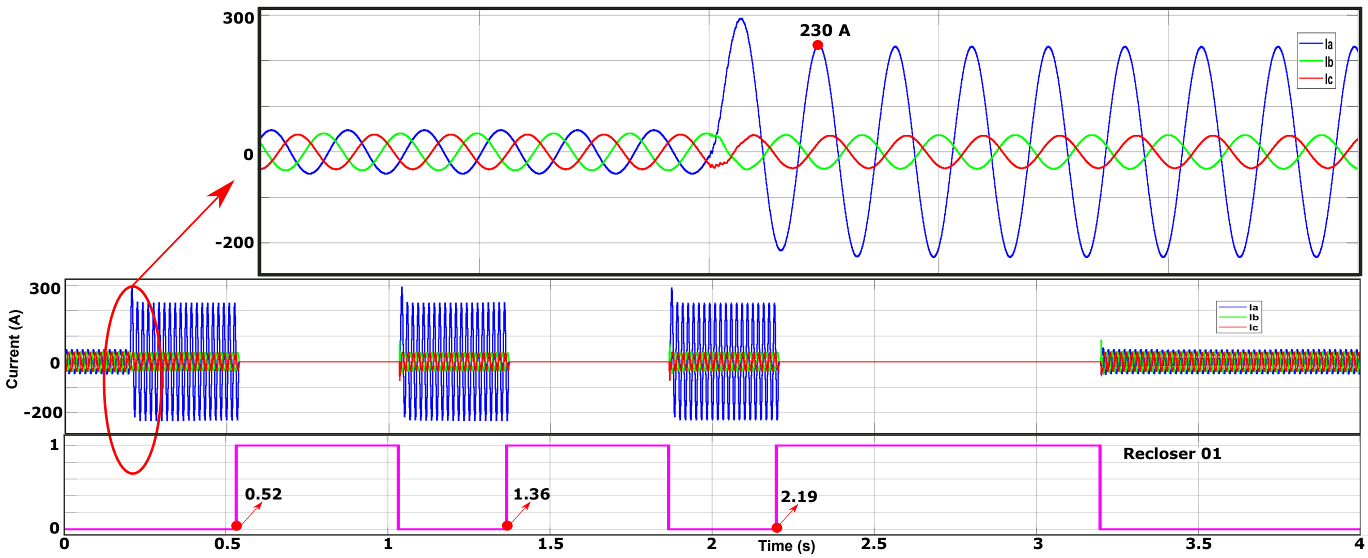

Fig. 8. Current in phases a, b, c and trip signal of recloser 01 for AG fault.

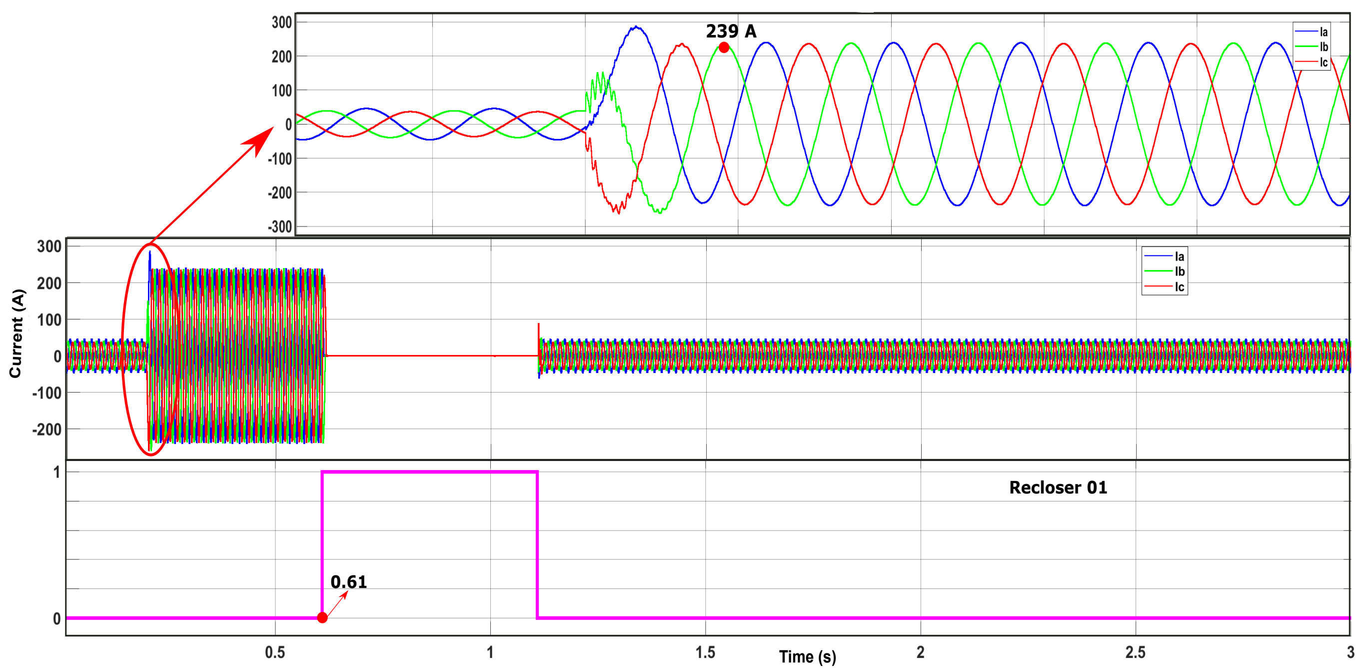

Fig. 9. Current in phases a, b, c and trip signal of recloser 01 for ABCG fault.

the recloser was responsible for the permanent opening of the section under fault, as shown in Fig. 10. The total time taken to identify and isolate the fault was 5.45 s.

B. Recloser 02 Analysis

Simulated faults to assess the performance of the recloser 02 model are described in subsections IV-B1, IV-B2, and IV-B3, respectively.

1) Scenario 1 - AB Fault: According to [25], overhead distribution lines are prone to temporary two-phase faults. In this study, the behavior of recloser 02 was analyzed for a short-duration two-phase AB fault at the beginning of the section between busbars 844-846 which started at 0.2 s, lasting 1.8 s for a fault resistance of 0.001 Ω. Recloser 02 performed a crucial role to restoring the power supply. According to Fig. 11, the device tripped three to re-establish the network, with times of 0.29 s, 0.89 and 1.55 s, after the start of the fault, with a short-circuit current of around 202 A. The fault was stinguished during the reclosing time, no further trips were required, which ensured the EDS integrity.

2) Scenario 2 - BG fault: To assess the the recloser's behavior in the event of a permanent fault, a single-phase BG fault was simulated at the beginning of the section between busbars 836 - 860, with a fault resistance of 0.001 Ω.

The fault started at 0.2 s, as shown in Fig. 12. Recloser 02 performed as expected, isolating the section around 3.3 s

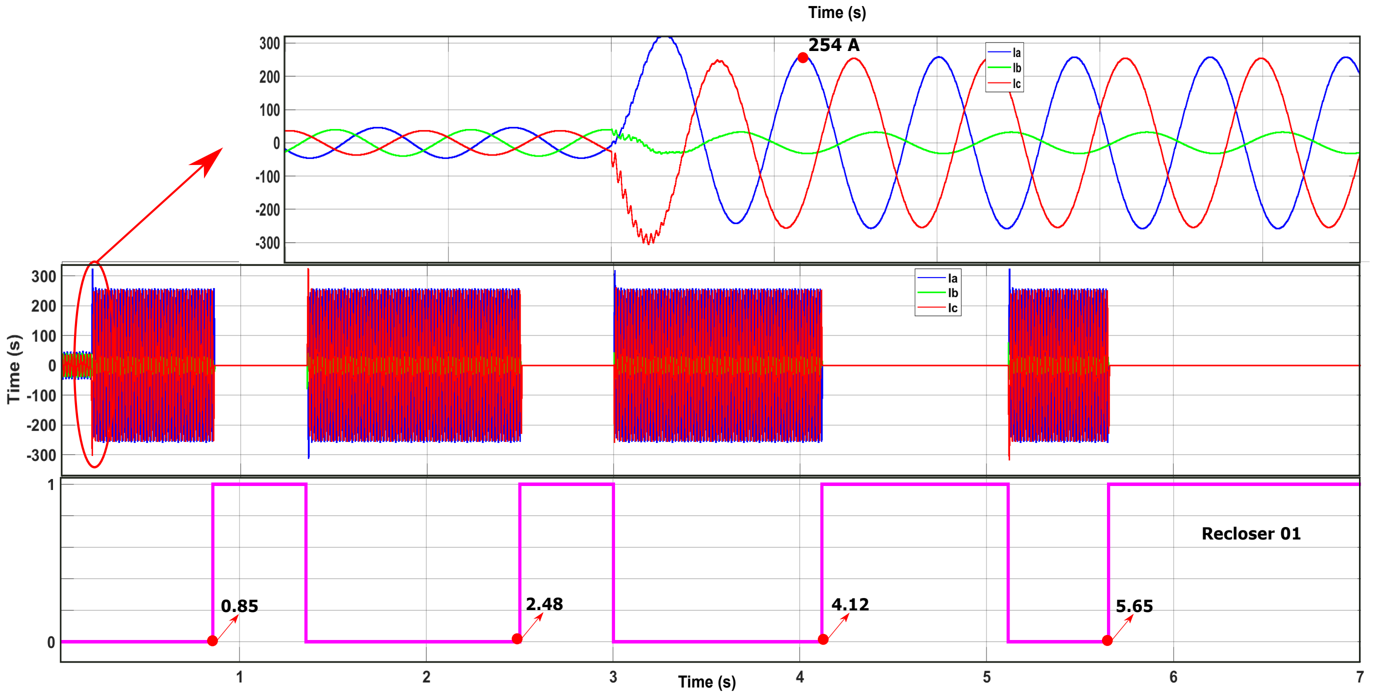

Fig. 10. Current in phases a, b, c and trip signal of recloser 01 for an ACG fault.

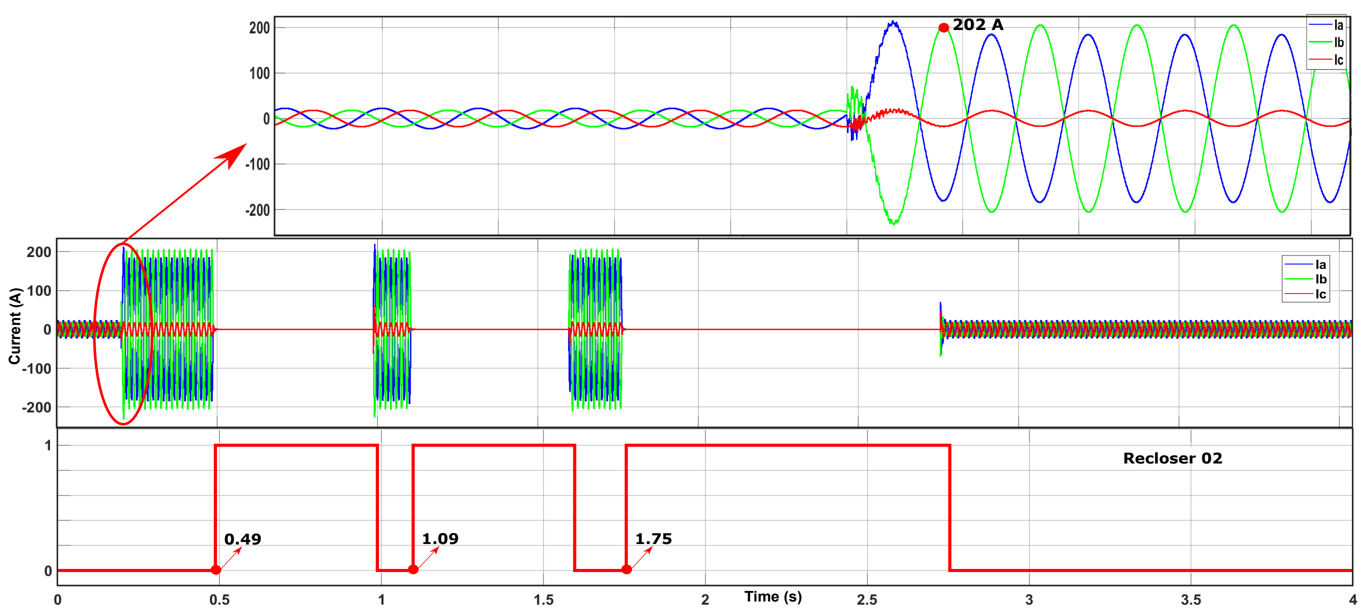

Fig. 11. Current in phases a, b, c and the recloser 2 trip signal for the AB fault.

after the fault began, in accordance with the estimated time from the time versus current characteristic curve. The device triggered four times, at 0.34 s, 1.19 s, 2.04 s and 3.3 s, for a fault current of around 178.14 A.

3) Scenario 3 - ABC Fault: Based on the severe damage that a three-phase fault can cause to the electrical system, a behavior analysis on recloser 02 was conducted in the face of a permanent three-phase fault at the end of the section between busbars 842 - 844, with a fault resistance of 0.001 Ω.

According to Fig. 13 the fault started at a time of 0.2 s and recloser 02 operated with times of 0.12 s, 0.72 s, 1.31s and 2.4 s after the start of the fault. The short-circuit current identified by the device was of around 253 A and a total operation time of 2.4s, which was aligned with the expected time based on the time versus current curve.

V. Conclusions

The coordination of the EDS's protection equipment is of the almost importance to ensure the continuous provision and quality of the service to the customer. Nowadays, this activity is conducted with intensive computer simulation usage, it is essential to study and validate the equipment models on an

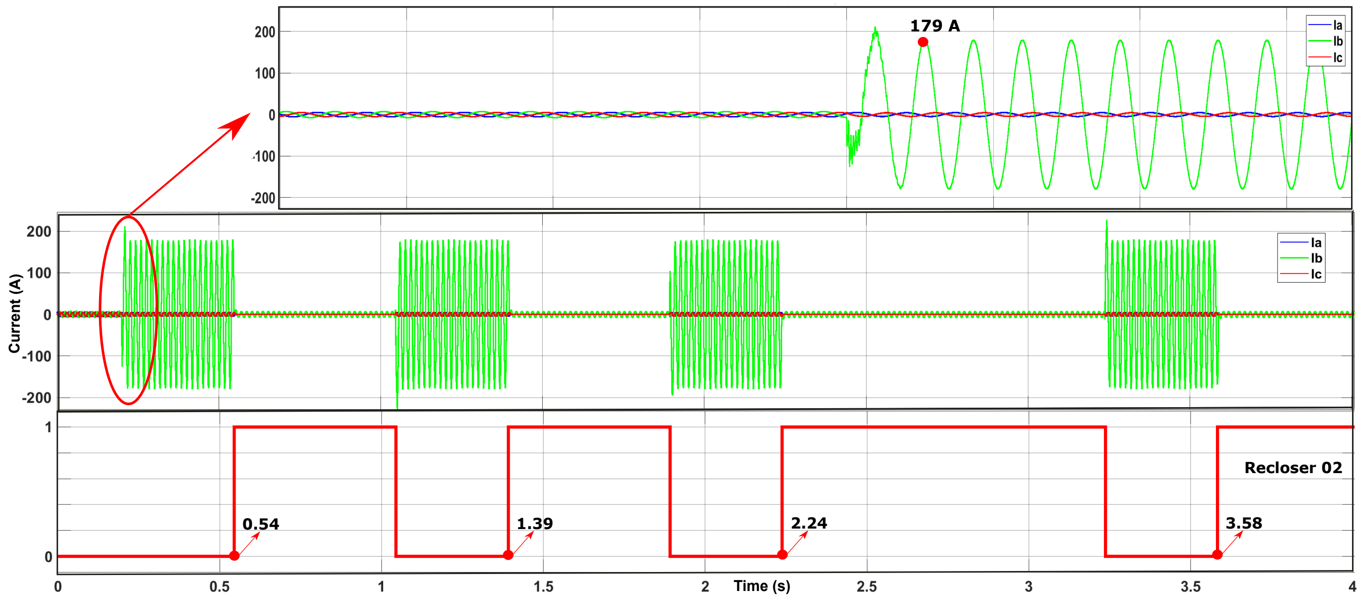

Fig. 12. Current in phases a, b, c and the trip signal of recloser 2 for BG faults.

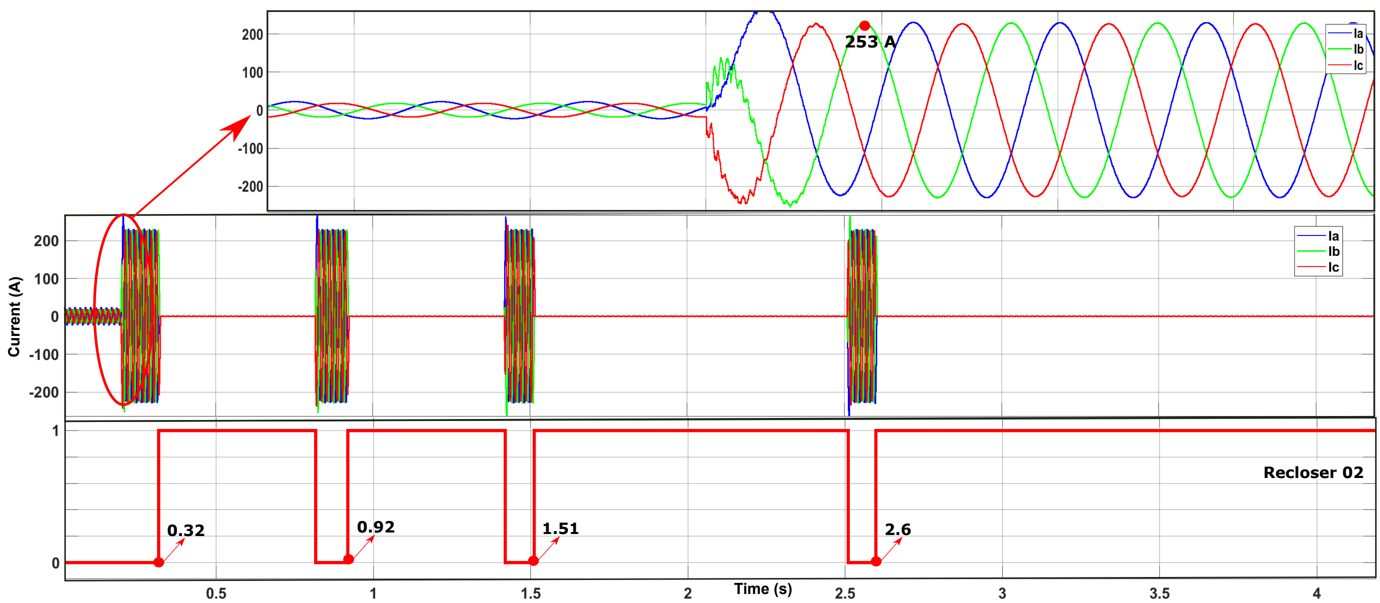

Fig. 13. Current in phases a, b, c and behavior of recloser 2 for ABC fault.

ongoing basis so that the results adhere to the reality observed in the field. In this context, the article models the behavior of a digital recloser using Simulink/Matlab® software, which is widely used in Brazilian academia. However, it has the disadvantage of not offering protection device models such as reclosers and relays.Therefore, this work aims to contribute to the set of tools available in the software for analyzing EDS protection systems.

Since the IEEE 34-bar is widely used for EDS protection studies, it was used to assess the behavior of the modeled device. Within this context, different faults were applied to the system and the behavior of the modeled reclosers was analyzed. Finally, it was found that the devices showed similar behavior to the reclosers implemented by the power utilities, acting within the time specified by the time versus current curve.

The devices provided adequate results in all the cases analyzed, regardless of their fault type and duration. In temporary faults, the reclosers acted and re-established the power supply, and for permanent faults, the device carried out the four planned operations and consequently opened the section of the fault.

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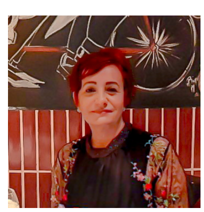

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