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The dynamic behavior of a solid state transformer (SST) during recloser operation in distribution systems

Fahd Amin Hariri

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THE DYNAMIC BEHAVIOR OF A SOLID STATE TRANSFORMER (SST) DURING RECLOSER OPERATION IN DISTRIBUTION SYSTEMS

by

FAHD AMIN HARIRI

A THESIS

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Approved by

Dr. M. Crow, Advisor
Dr. J. Kimball
Dr. M. Ferdowsi

ABSTRACT

Electrical power systems are continuously facing increasing electrical power demand in the last years to meet the requirements of modern life style. In order to satisfy such needs electricity authorities are taking appropriate measures to enhance the performance of power networks. One of the solutions to meet the customer's demands for energy was the trend to use the renewable energy. The increasing use of renewable energy and other distributed generation sources made the electrical grid more complex. Many researches have been carried out to find out solutions to overcome this complexity. One of these researches – which was on a Solid-State Transformer technology- attracted scholars in recent years. The motivation for this thesis is to study the behavior of the SST under operation of protective devices such as recloser and fuse.

In order to investigate the dynamic behavior of the SST, a recloser model has been designed and implemented in PSCAD®/EMTDC™. The accuracy of the model has been verified through comparison between simulation and theoretical results. Then, the recloser model has been deployed in a small distribution system along with the SST. Finally, different SLG fault scenarios have been applied and the SST has been investigated.

DEDICATION

I dedicate this work to my parents,

my wife,

my daughters.

Your love means everything to me

ACKNOWLEDGMENTS

First and foremost, I would like to express my deep thanks to my advisor Prof. Mariesa Crow for her serious efforts through all steps of working in this project, which could not be realized without her patient efforts. I am also grateful to Dr. Jonathan Kimball and Dr. Mehdi Ferdowsi for serving as members of my committee.

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1. INTRODUCTION

Since the development of a commercially practical transformer by William Stanley in 1886, the transformer has been considered one of the most important devices in modern electric power systems. The widespread use of electrical power today would not have been possible without the transformer. Transformers act as “the glue” that hold the entire system together by stepping up line voltages for transmission over long distances, and then stepping the voltages down to the levels required by end users [1] [2].

Conventional distribution transformers, or so-called copper-and-iron based transformers and line-frequency transformer (LFT), have several advantages such as low cost, simple construction, high reliability, and high efficiency. On the other hand, these transformers have many disadvantages such as a heavy and bulky size, considerable voltage drop under load, power quality issues, lack of self-protection, environmental issues regarding leaking of oil, and inability to control voltage and current [3] [4].

Electrical power systems have faced increased use in recent years to meet the requirements of the modern life style. In order to satisfy these needs, electricity authorities are taking measures to enhance the performance of power networks. One of the solutions to meet the customer's demands for energy is the trend to use increased amounts of renewable energy. The additional use of renewable energy and other distributed generation sources have made the electrical grid more complex. Considerable research effort has been applied to find solutions to overcome this complexity. The effort to develop the solid-state transformer has attracted scholars in recent years. This new technology has many advantages compared with the traditional line frequency transformers (LFT) such as reduced size and weight, instantaneous voltage regulation, power factor correction, provides ports for the proper integration of distributed generation (DG) and energy storage, and more [5] [6]. For example, Figure 1.1 shows a size comparison of a traditional transformer and the high-frequency transformer used in solid-state transformers.

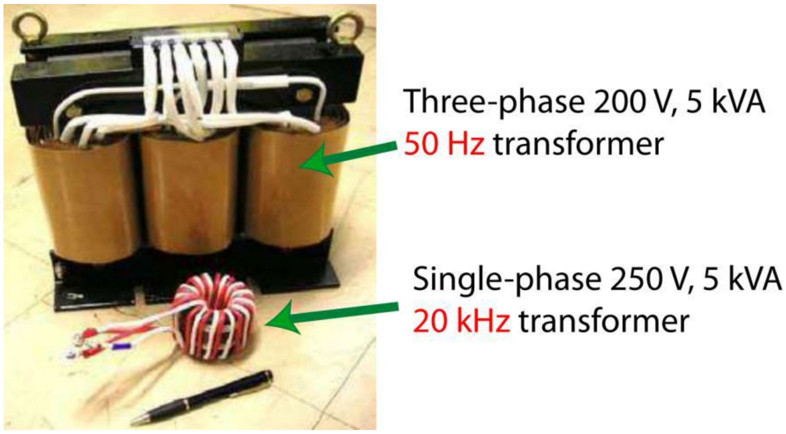


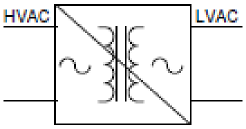
Figure 1.1. Comparison between a LFT and a high-frequency transformer [4]

Solid state transformers can be used instead of the conventional transformer in multiple applications including locomotives and other traction systems, offshore energy generation, and smart grids [5].

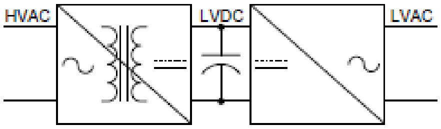
Many papers have been published on different aspects of SSTs. The first SST was proposed by James Brooks in 1980 [5]. This effort was followed by Resischi in 1995, but both of these prototypes were operated at power and voltage levels below utility distribution level [3]. Since that time, many studies on SST technology have been performed and published. Each proposed SST had both advantages and disadvantages depending on the philosophy used by researchers. A comprehensive comparison of all SST topologies has been conducted in [3]. According to [7], all SST topologies can be grouped into four categories:

a) Single-stage with no DC link;
b) Two-stage with low voltage DC (LVDC) link;
c) Two-stage with voltage DC (HVDC) link;
d) Three-stage with both HVDC and LVDC.

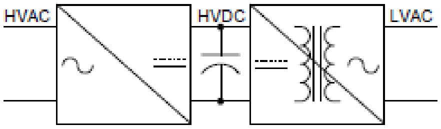
Figure 1.2. illustrates these four basic categories.



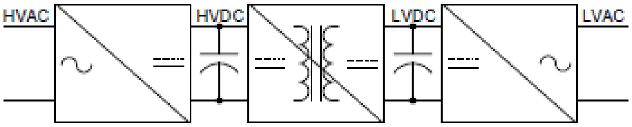
a) Single-stage SST with isolated ac-ac



b) Two-stage SST with isolated ac-dc



c) Two-stage with isolated dc-ac



d) Three-stage with isolated dc-dc

Figure 1.2. SST configurations [7]

The solid state transformer topology used in this research is the three-stage DAB designed by a group of researchers at North Carolina State University, Missouri University of Science and Technology, and Arizona State University as part of the NSF-sponsored Future Renewable Electric Energy Delivery and Management (FREEDM) Engineering Research Center.

As shown in Figure 1.3, the solid state transformer consists of three stages [4] [8]:

- AC/DC rectifier
- DC/DC Dual Active H-Bridge (DAB) converter with a high frequency transformer
- DC/AC inverter

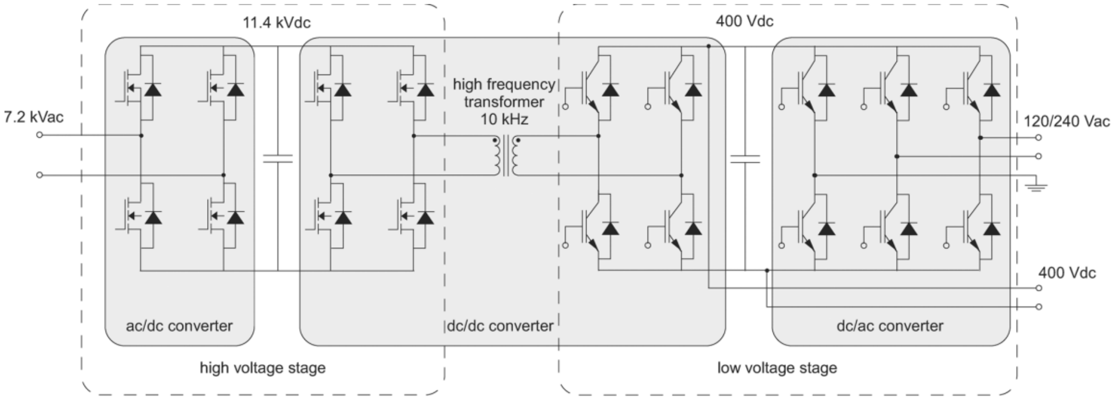


Figure 1.3. Topology of a Solid State Transformer [8]

Since SST technology is relatively new and the knowledge of its behavior in the grid is rather limited, more investigation is needed to gain more insight into the SST behavior. This thesis will focus on developing a PSCAD model for an autorecloser that can be used for simulating the operation of the recloser under fault conditions in a distribution system and the effect of those on the SST dynamic behavior.

1.1. PROBLEM STATEMENT

The dynamic behavior of a solid-state transformer (SST) during the operation of protective devices, such as autoreclosers, in a distribution system is not yet understood.

1.2. RESEARCH OBJECTIVE

The objective of this research project is to design a PSCAD model for an autorecloser and deploy it along with SST in a distribution system to investigate the dynamic behavior of SST under fault conditions.

1.3. RESEARCH APPROACH

This research is structured as follows:

Section 1 introduces the importance of conventional transformers, advantages and disadvantages of conventional transformers, the motivation of the solid state transformer, and a literature review of the SST.

An overview of distribution systems, protection of MV and LV distribution systems, protective devices such as fuses, reclosers, sectionalizers, and overcurrent relays are presented in Section 2.

In Section 3, the modeling of a single-phase autorecloser in PSCAD®/EMTDC™ is developed. The simulation and comparison of the recloser model with theoretical results are presented.

In Section 4, the SST model along with the recloser model is used to simulate different fault scenarios in order to study the behavior of the SST during the operation of protective devices. The simulation results are presented and discussed.

Conclusions and future work are presented in Section 5.

2. OVERVIEW OF DISTRIBUTION SYSTEM PROTECTION

Power plants generate electricity using different sources such as coal, gas, wind, solar and hydro. The electrical grid receives the generated electricity and transfers over long distances through overhead, underground, and sub-sea cable systems. When it reaches load centers, distribution networks carry the electrical power to industrial, household and commercial end users [9]. Figure 2.1 shows an overview of the electric system.

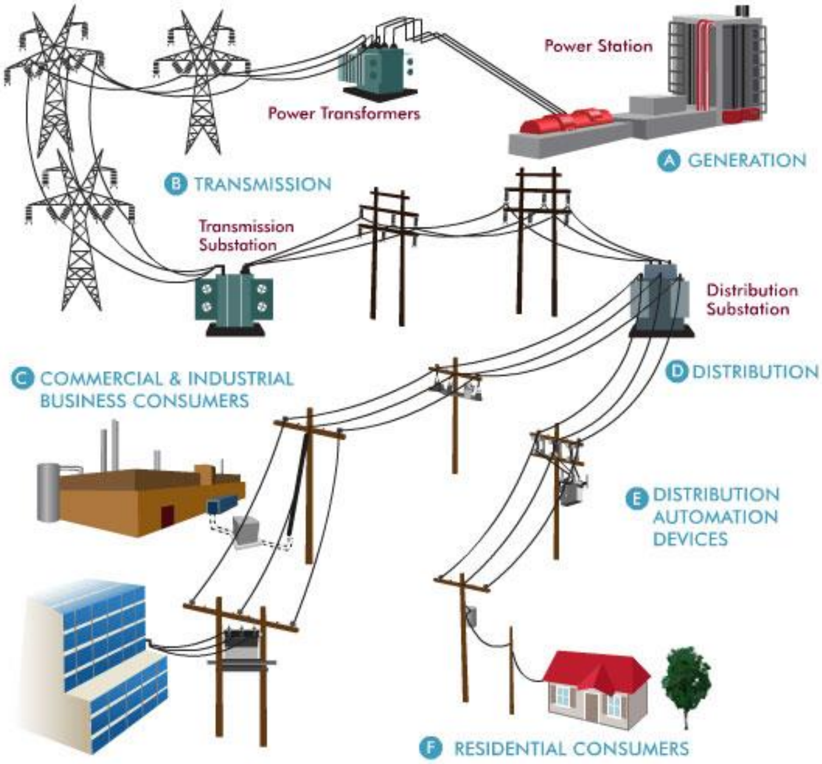


Figure 2.1. Basic Structure of the Electric System [10]

The widespread use of electrical power as we see it today would not have been possible without the development of a commercially practical transformer by William Stanley in 1886. At that time, the first full AC power system, built by William Stanley and funded by Westinghouse, was demonstrated using step up and down transformers [1] [11] [12]. Since the development of the transformer, transformers have become essential for all power systems [13]. Distribution systems have hundreds of distribution transformers which, in general, are used to step down primary system voltages, known as medium-voltage in the 2.4-34.5 kV range, to utilization voltages, also called low-voltage in the 120 – 600 V range [2][11] [14]. Therefore transformers play an important role in power systems and they act as “the glue” that holds the entire system together by stepping up line voltages for transmission over long distances, and then stepping the voltages down to the levels required by end users [2]. Figure 2.2 shows a simple one-line diagram of a distribution system. Figure 2.3 shows the original distribution transformer and Figures 2.4 and 2.5 show modern commercial distribution transformers.

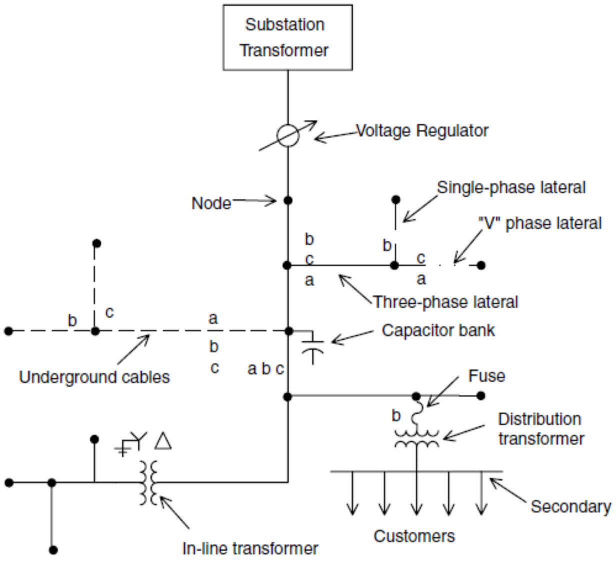


Figure 2.2. Simple distribution feeder [15]

Figure 2.3. Stanley's first transformer which was used in the electrification of Great Barrington, Massachusetts in 1886 [13]

Figure 2.4. Single-phase distribution transformer, primary voltage up to 36 kV, range up to 315 kVA by ABB [33]

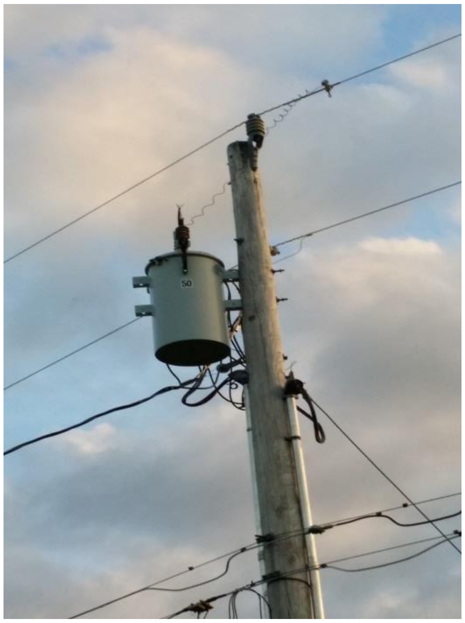


Figure 2.5. Single-phase distribution transformer, Rolla, MO, USA

2.1 PROTECTION OF THE DISTRIBUTION SYSTEM

Distribution networks must be adequately protected against faults in order to minimize outage times as well as to avoid damage to equipment. According to [16] [17], most faults in medium-voltage distribution systems are single-line-to ground and occur from various causes such as falling branches, ice, lightning and so forth. Single-line- to ground faults represent 70% - 80% as percentages of occurrence in distribution systems. Therefore, in this research, we will focus our study on this type of fault.

2.2 PROTECTION OF MEDIUM-VOLTAGE DISTRIBUTION SYSTEMS

A wide variety of devices are used to protect distribution networks. The most important protective devices used on medium-voltage distribution systems are [16]:

- Fuses;
- Reclosers;
- Sectionalizers;
- Overcurrent relays, as in [18].

2.2.1 Fuses. The fuse was invented in 1890 by Edison and it is an inexpensive form of protection against excessive current. Since the fuse is relatively maintenance-free which, along with its low cost, makes it widely used in most utility distribution systems to protect transformers and lateral branches [19] [20].

According to [17], IEEE defines a fuse as “an over-current protective device with a circuit-opening fusible part that is heated and severed by the passage of the overcurrent through it." The fuse element is generally made of metals such as tin or silver placed inside a porcelain or glass tube. In case of a fault, the metal melts which leads to the interruption of the current. This action produces de-ionising gases that accumulate in the tube and the fuse automatically expels out of the tube, indicating that a fault has occurred on the line. Once the fuse melts due to a fault, it needs to be replaced before the protected circuit can carry load again [20] [21]. Figure 2.6 shows a typical utility expulsion fuse.

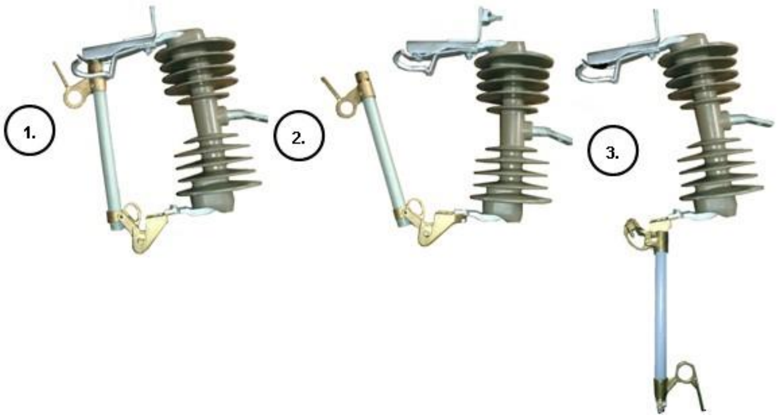


Figure 2.6. Typical utility fuse cutout with an expulsion fuse [22].

The operating time due to fault current depends on the magnitude of the fault current. This time is typically about one half-cycle. Because of the operation of the fuse, the fault current is cut off before the current can reach the maximum prospective value [19] [21].

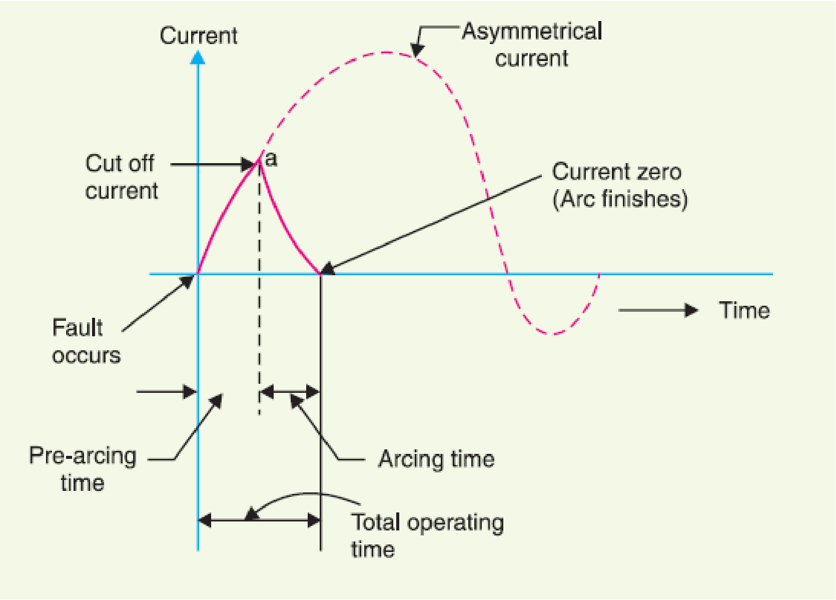


Figure 2.7. Current characteristic for short-circuit cut off by a fuse [19].

Two basic kinds of fuse used in power systems are [20]:

- Expulsion fuses;
- Current-limiting fuses.

Expulsion fuses are the more widely used protective devise on distribution systems due to their low-cost and maintenance-free operation. This fuse type is designed to carry a normal load current and interrupt the faulted part of the circuit. As shown in Figure 2.7, this type of fuse cutouts as short as one-half-cycle for high fault currents. In general, the operating time of the fuse depends on its distinctive inverse time-current characteristic (TCC). The higher the fault current, the faster the fuse melts [11] [20].

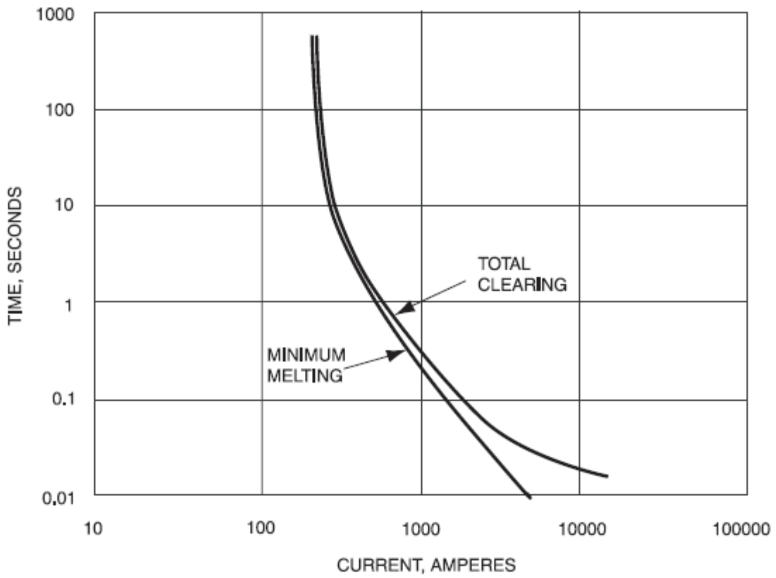


Figure 2.8. Typical TCC curves for an expulsion fuse [23].

As shown in Figure 2.8, the TCC consist of two curves, the minimum melting curve and the maximum total clearing melting curve. These two curves are plotted on a log-log scale with current on X-axis and time on Y-axis. The minimum melting curve is required for selecting the appropriate fuse. Whereas the maximum total clearing melting curve is required for coordination with upstream devices [20] [23].

Current-limiting fuses are another type of fuse used in distribution networks to interrupt faulted sections of the system. They have a unique ability to reduce the fault current magnitude and are widely used for protection of equipment in areas where fault currents are expected to be very high. Because of the high-cost of current-limiting fuses compared to expulsion fuses, the use of these fuses are generally restricted to locations where the fault current is expected to be in the range of 2000A to 3000A [11] [20]. Figure 2.9 shows the location of different types of fuses.

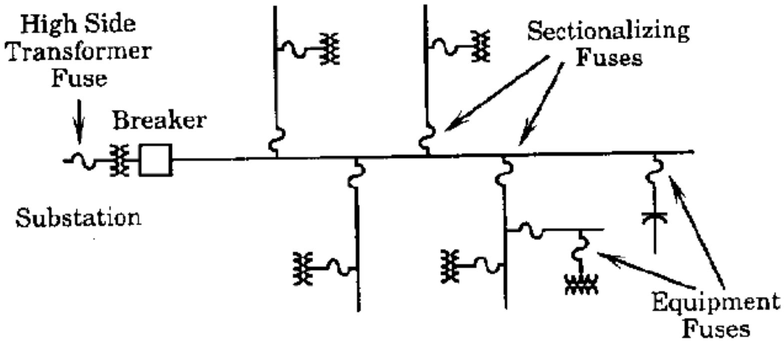


Figure 2.9. Application of fuses on distribution circuits [24]

2.2.2 Reclosers. In distribution system, especially in rural areas, overhead lines are used. The spacing between conductors is relatively close [25]. Therefore, depending on the nature of the distribution system, approximately 80% - 95% of the faults are temporary in nature. Transient faults usually occur if phase conductors touch another phase or ground momentarily caused by lightning, vines, trees, birds or other animals [14]. This type of fault lasts, at the most, for few cycles or seconds. Thus, using a recloser will improve the reliability and the power quality of distribution systems by preventing them from being left out of service for temporary faults [18] [20] [26]. A recloser is defined by IEEE as “a device that controls the automatic reclosing and locking out of an AC circuit breaker” [27].

The recloser is basically an overcurrent protective device that has the ability to detect overcurrent conditions on either phase or ground conductors. It trips and recloses a pre-programmed number of times in an attempt to reenergize the line. Reclosers are designed and built in either single-phase or three-phase units [14]. Single-phase reclosers are used when the load is predominantly single-phase and also can be used on three-phase feeders [17] [18]. The advantage of a single-phase recloser unit is better service reliability as compared to three-phase reclosers.

The operation of a recloser depends on its time current curve (TCC). Each recloser has two TCCs: the fast and delayed curves. Therefore, a recloser can be pre-programmed to interrupt a fault current instantaneously or slowly as required, such as in a fuse saving operation. The recloser is on the fast tripping setting if it operates on the fast curve. Similarly, it is considered to be on the delayed setting if it operates on the delayed curve. Figure 2.10 shows a fault current on a typical TCC of a recloser. The recloser will interrupt within 0.04 s on the instantaneous setting or within 1.3 s if on the time-delay setting [20].

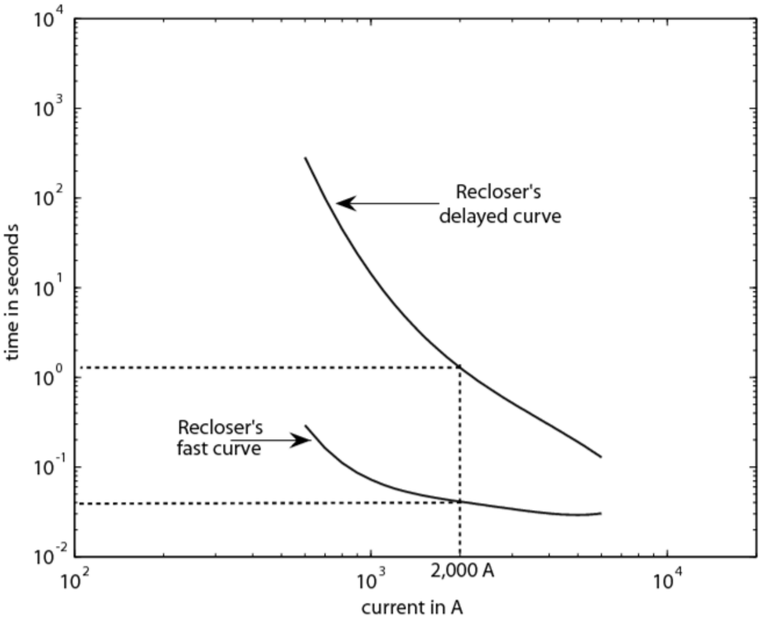


Figure 2.10. Time-current characteristics of a recloser: fast and delayed curves [20]

Typically, reclosers can be set to have up to four open-close operations prior to lockout. Different operation sequences can be set such as [14]:

- 2-fast, 2-time delay operations;
- 1-fast, 3-time delay operations;
- 3-fast, 1-time delay operations;
- 4-fast operations;
- 4-time delay operations.

The first two are the most common sequences used in the USA [20]. Figure 2.11 shows a typical sequence of a recloser operation for a permanent fault.

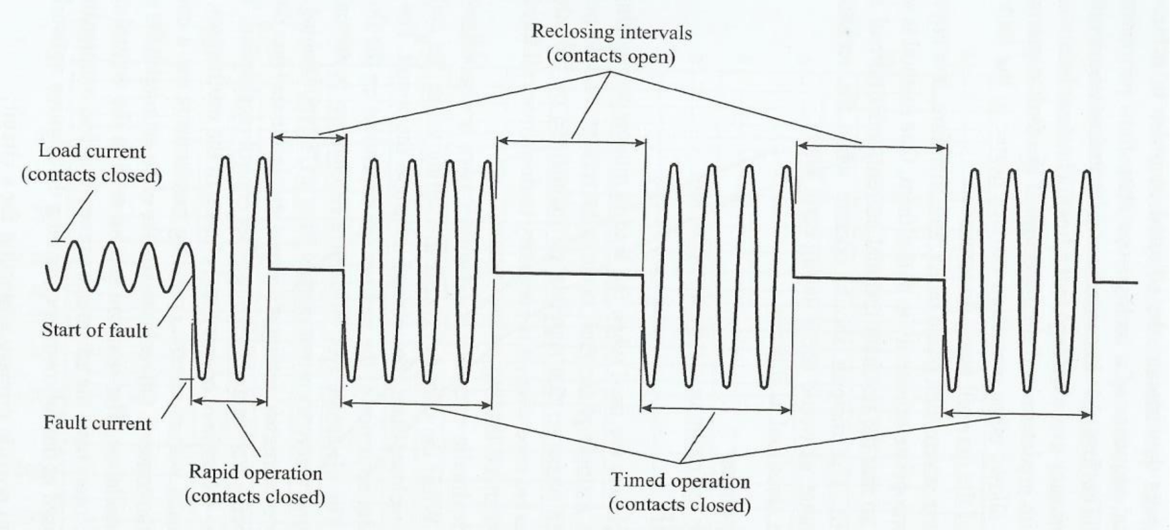


Figure 2.11. Typical sequence for recloser operation [18].

According to [18], reclosers are used on a distribution system at the following locations as shown in the Table 2.1 below.

Table 2.1. Reclosers locations and functions on a distribution network.

Location	Function
Substations	"To provide primary protection for a circuit" [18].
Main feeder circuits	To prevent the loss of the entire circuit due to a fault at the end of the circuit
Laterals (or branches)	To protect the main circuit due to faults on the branches

2.2.2.1 Recloser-Fuse coordination: fuse saving. Selectivity (also known as relay coordination) is one of the objectives of system protection. These objectives are: reliability, selectivity, speed of operation, simplicity, and economics. Selectivity can be defined as "maximum continuity of service with minimum system disconnection" [17].

In distribution systems, selectivity is normally expected between upstream and downstream devices. In some cases, the line recloser is set to trip for faults beyond a downstream branch fuse, before the downstream fuse operates. This practice is known as a "fuse saving" scheme because it can help reduce expensive fuse replacement and customer extended outage time. The basic idea of fuse saving is to set the recloser to trip on fast (instantaneous) operation before the fuse branch can blow, and the recloser is then reclosed after a very short delay. If the fault persists, the recloser switches to a time-delay curve. This gives the branch fuse a chance to melt and isolate the fault. After isolating the faulted branch, customers connected to that branch will experience an outage, while customers downline from the recloser will be restored. Customers on other feeders will experience momentary interruptions as a slight blink due to the operation of the recloser [20] [28]. Figures 2.12 and 2.13 show fuse and recloser coordination.

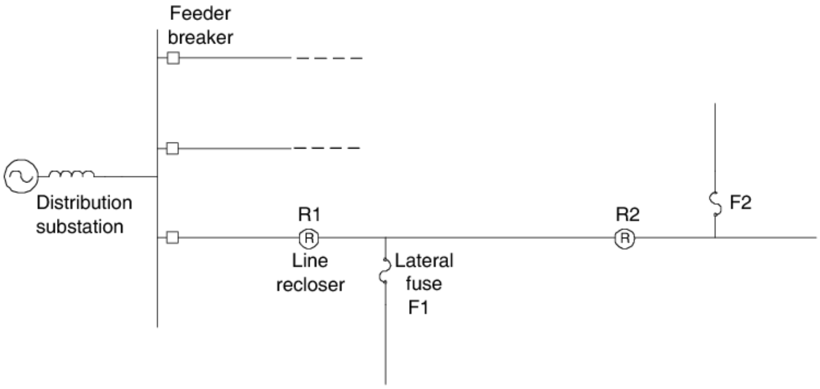


Figure 2.12. Recloser and fuses on distribution circuits [20]

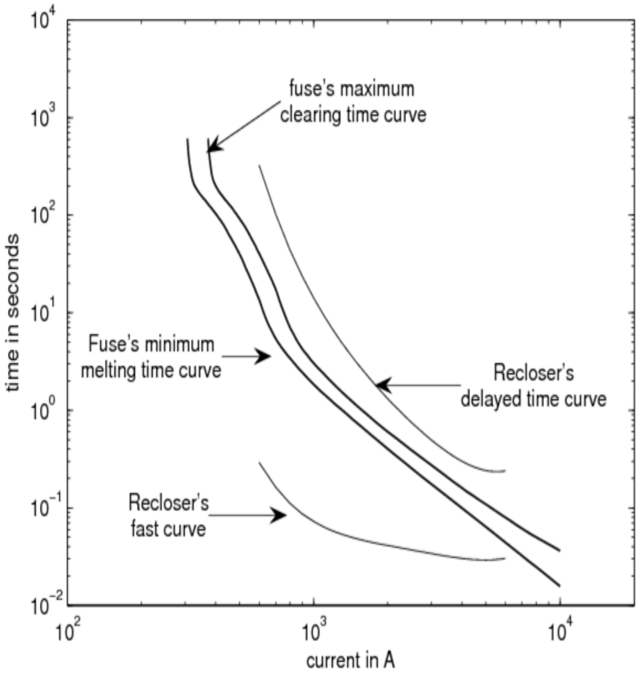


Figure 2.13. Time-current characteristics curves for recloser-fuse coordination [20]

2.2.3 Sectionalizers. A sectionalizer is a special circuit breaker that is not rated to interrupt fault current. Its operation depends on the number of times an upstream protective device, such as a recloser or a circuit breaker, has tripped. In other words, the sectionalizer functions according to the “instructions” of a recloser [16] [17].

The principle operation of the sectionalizer is to open the main electrical circuit while it is de-energized after a pre-selected number of interruption operations by the upstream protective device. Sectionalizers have an advantage over fuses that they can restore the service after a fault has been removed without replacing any element. Also, the sectionalizer is easy coordinated with other protective devices since it does not have time-current characteristics such as the fuse [14] [16].

2.2.4 Overcurrent Relays. Overcurrent relays are used to protect almost all distribution circuits. Overcurrent relays use inverse time characteristics in their operations. That means the overcurrent relay responds to the magnitude of its input current. If an instantaneous overcurrent relay is used, the relay will respond to the magnitude of its input current immediately. Furthermore, if a time-delay overcurrent relay is used, the relay response will be subjected to an intentional time delay [12].

IEEE defines the instantaneous overcurrent relay as “a device that operates with no intentional time delay when the current exceeds a preset value” [27]. The inverse-time overcurrent relay is defined as “a device that functions when the ac input current exceeds a predetermined value, and in which the input current and operating time are inversely related through a substantial portion of the performance range” [27].

Figure 2.14. shows standardized characteristics of overcurrent relays. More details of the mathematical formula used to calculate the operating time will be discussed in Section 4.

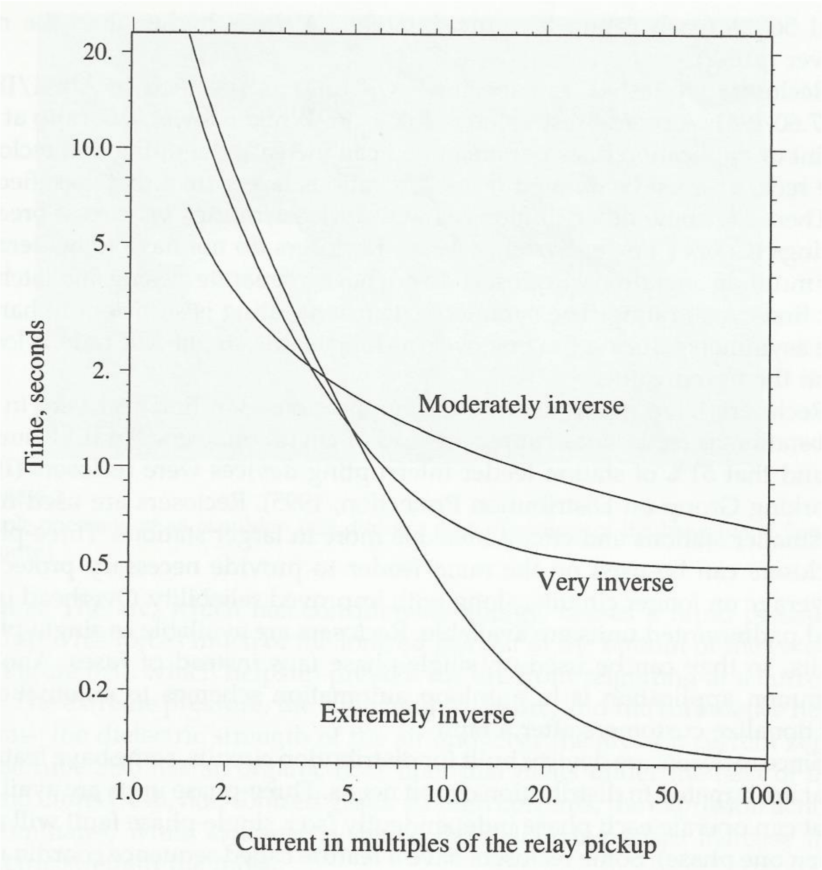


Figure 2.14. Relay curves following the IEEE standardized characteristics for a time dial = 5 [11]

2.3 PROTECTION OF LOW-VOLTAGE DISTRIBUTION SYSTEM

As discussed earlier in this section, electrical energy is transported to the customer by HV substations through MV networks and finally by LV circuits. The most common low-voltage systems used in North America are shown in Table 2.2. [16].

Table 2.2. The most common low-voltage systems used in North America.

#	LV System	Purpose
1	Single-phase, 2-wire, 120 V	For very small loads.
2	Single-phase, 3-wire, 240/120 V	• Small loads, e.g. lighting, can be operated at 120 V. • larger loads like stoves and refrigerators can be operated at 240 V.
3	Three-phase, 4-wire, 208/120 V	For commercial buildings and small industries.
4	Three-phase, 3-wire, 600 V system	For factories with large motors (up to 500 hp)
5	Three-phase, 4-wire, 480/277 V System	Used in large buildings and commercial centers.

The protection devices used to protect the LV system are usually fuses or circuit breakers. As shown in Figure 2.15, both live lines are protected by fuses whereas no protective device is used with the neutral conductor.

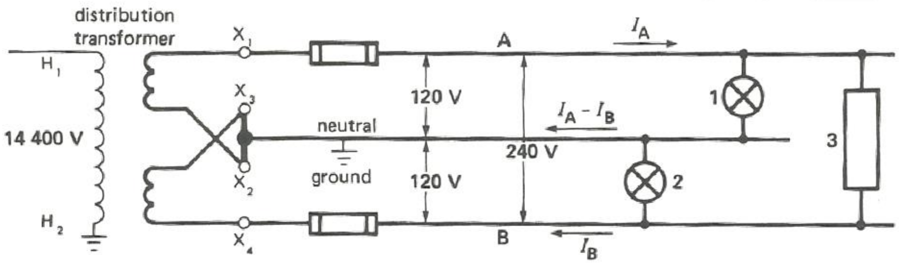


Figure 2.15. Single-phase 240/120 V distribution system [16]

3. MODELING OF A SINGLE-PHASE AUTORECLOSER IN PSCAD®/EMTDC™

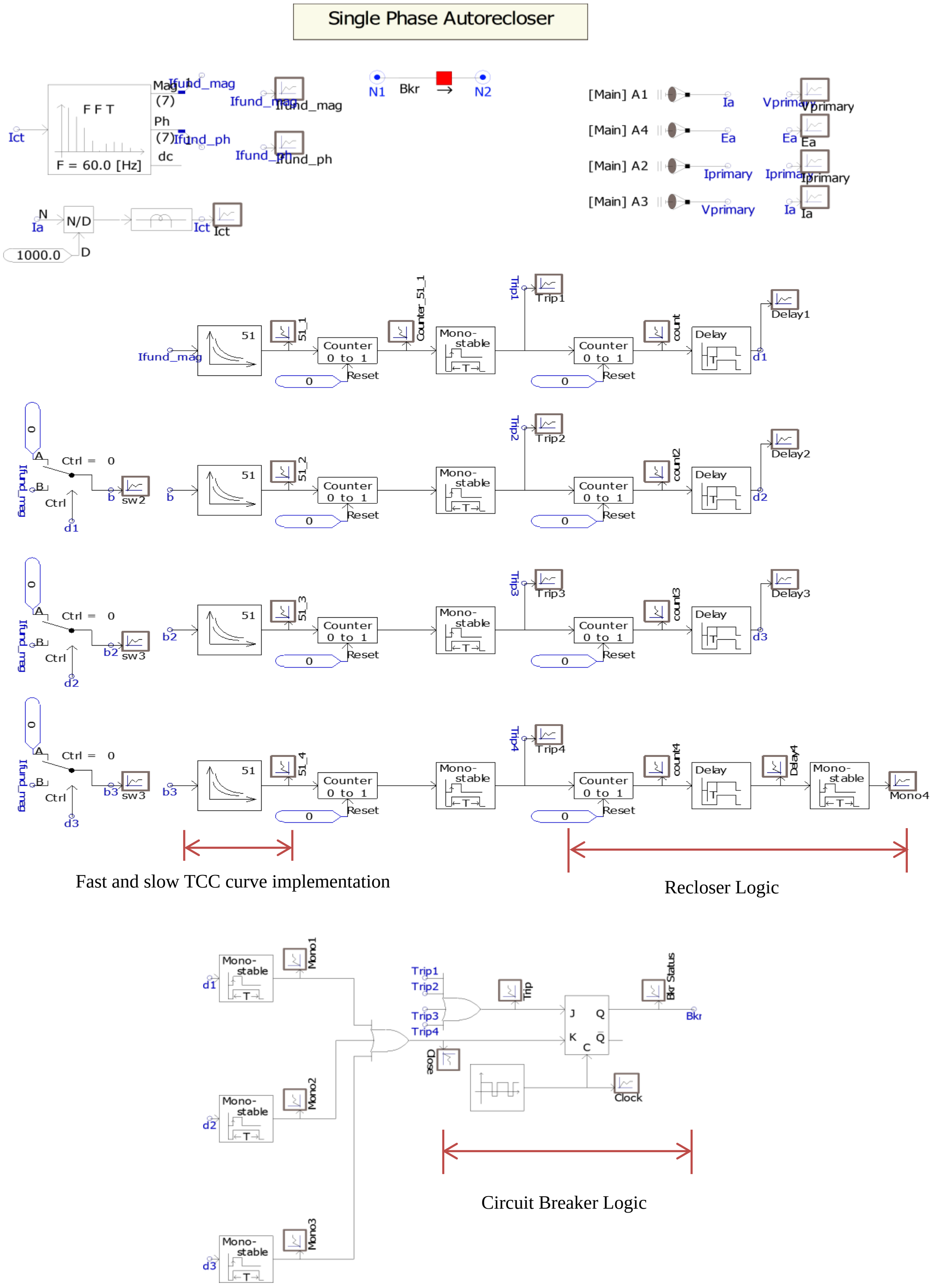
This section details the design of the recloser model in PSCAD®/EMTDC™. The performance of the model is illustrated by deploying it to protect a simple distribution system and the simulation results compared with theoretical results are presented.

The purpose of this model is to represent the operation of a recloser and then using this model to understand and study the behavior of the solid state transformer (SST) as shown in the next section. As discussed in Section 2, the recloser is basically an overcurrent protective device that has the ability to detect overcurrent conditions either on phase or ground conductors. It trips and recloses a pre-programmed number of times in an attempt to reenergize the line.

3.1 RECLOSER MODEL

The recloser model consists of a circuit breaker and an external control circuit. The tasks of the control circuit are defining the time needed to activate the inverse-time overcurrent relay depending on its time current curve (TCC) and sending a close signal to the circuit breaker after a reclosing time interval has elapsed.

The recommended control circuit for the recloser consists of overcurrent relays along with other components as shown in Figure 3.1. The list of all components used in the control circuit and their functions are described in Table 3.1.



Fast and slow TCC curve implementation

Recloser Logic

Circuit Breaker Logic

Figure 3.1. Autorecloser model

Table 3.1. Components used in the control circuit and their functions

#	*Component*	*Function*
1	Current Transformer	Producing a reduced current accurately proportional to the large primary current in the circuit.
2	Fast Fourier Transform (FFT)	Processing the input to provide the magnitude and the phase angle of the fundamental and its harmonics. [29]
3	Inverse Time Overcurrent Relay	Sending a trip signal to the trip circuit if the input to it reaches a pre-determined pickup current. The output is 1 if the input exceeds the pre-determined pickup current and is equal to 0 otherwise if less than that value. [29]
4	Counter	Counts the number of shots
5	Monostable Multivibrator	Changes a constant input signal into a pulse for a set time (Pulse Duration).
8	Timed ON/OFF Logic Transition (Delay)	This component models a time transition diagram. The delay output will pick up after the set delay time, even if the input goes low before the ON Delay time. [29]
9	Two Input Selector	"The output of this component will be either the signal connected to **A**, or the signal connected to **B**, depending on the value of **Ctrl"**[29].
10	OR Gate	This component will output the value 1 for a logical true, and 0 for a logical false. "Outputs logical true if any of its inputs receive a logical true" [29].
11	JK Flip Flop	Implementing the reclosing operation. The output states change depending on the value of the clock input **C**. "If **C** is chosen as falling, the output changes state only on the falling edge of a clock pulse. If it is chosen as rising, the output changes state only on the rising edge of a clock pulse" [29].
12	Signal Generator	"This signal generator will output a triangle wave or a square wave. The duty cycle can be altered to adjust the shape of the waveform" [29].

During normal operation, the source feeds the load through the recloser. The load current will be stepped down by the current transformer (CT) to a lower value that can be handled by the relay. If the input current to the inverse-time overcurrent relay is less than the set value, the relay will stay in monitoring mode.

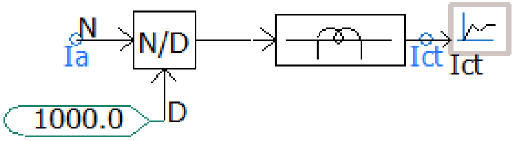


Figure 3.2. Current Transformer (CT) model

During abnormal circumstances, e.g. short circuit, the current flowing through the current transformer will be many times the load current. This fault current is stepped down through the CT and passed through a Fast Fourier Transform (FFT) element, shown in Figure 3.3, and then to inverse-time overcurrent relay. The function of the FFT element is processing the input to provide the magnitude and the phase angle of the fundamental and its harmonics because the overcurrent relay responds to the magnitude of its input current [12] [29].

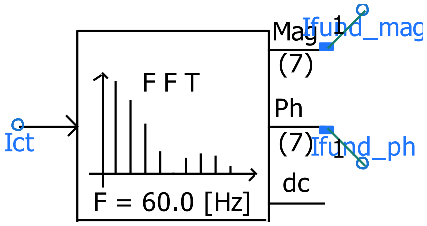
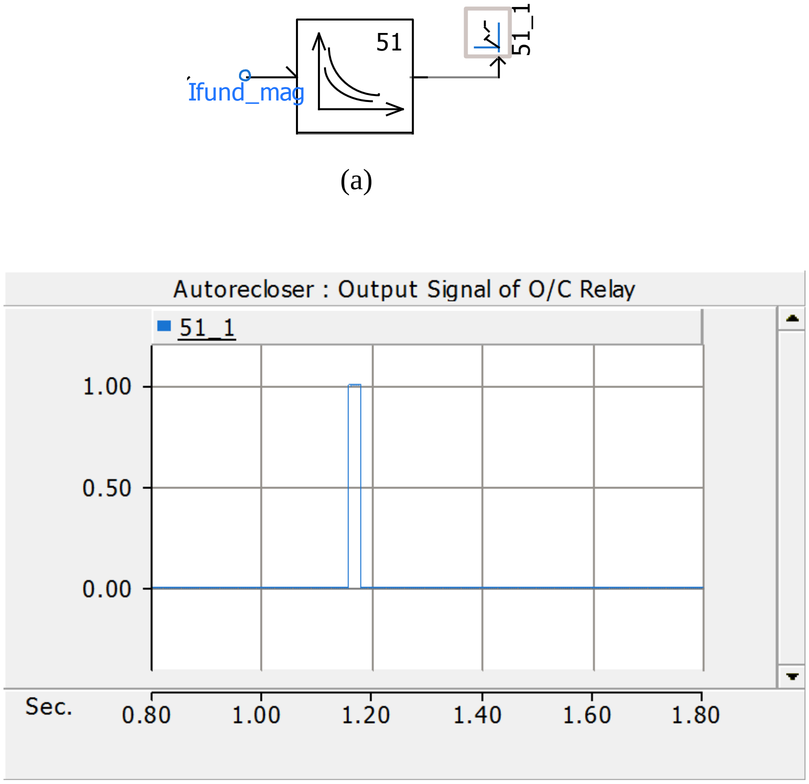


Figure 3.3. Fast Fourier Transform (FFT) model

The overcurrent relay, which functions as a comparison tool between two quantities, the operating quantity and the restraining quantity [30], will compare the input fault current by using the Time-Current Characteristics (TCC) curve. If the input current is greater than the set value, then the overcurrent relay will define the time needed to send a trip signal according to the TCC curve used. The output as shown in Figure 3.4 will be 1, which indicates that the system is experiencing a fault condition in the area protected by the overcurrent relay.

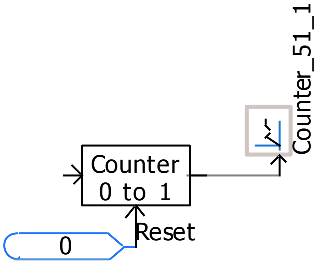


(a)

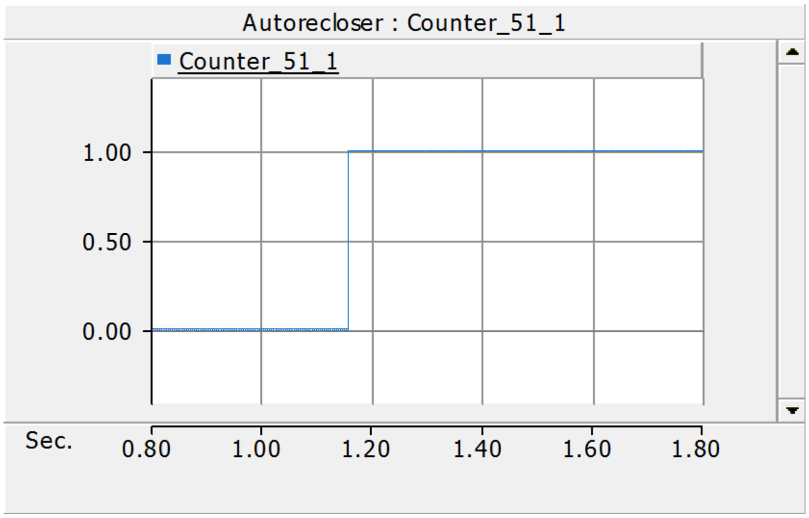
(b)

Figure 3.4. (a) inverse-time overcurrent model, (b) Output signal of the inverse-time overcurrent element

The output signal of the inverse-time overcurrent element is fed into a counter in order to limit the number of trip signals from the overcurrent element to no more than one trip signal. Figure 3.5 shows the output of the counter element.



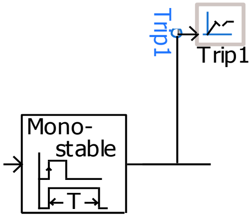
(a)



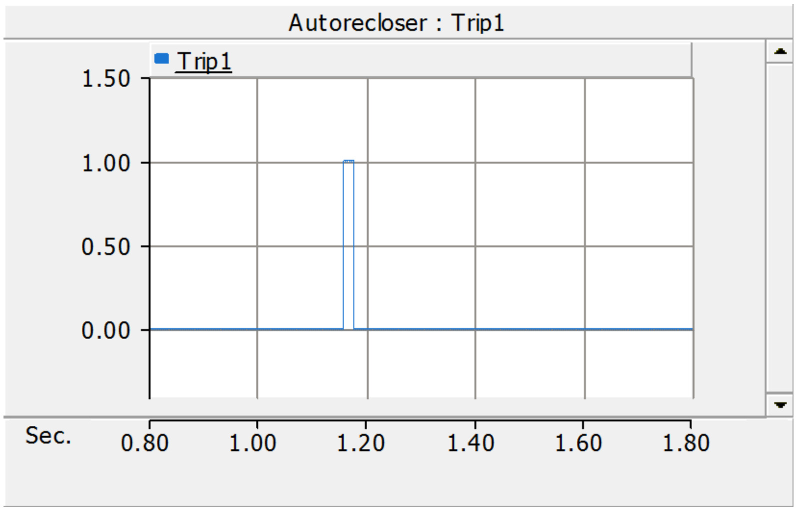
(b)

Figure 3.5. (a) Counter element, (b) Output signal of the counter element

In order to send a trip signal to the breaker, the output of the counter is fed into the monostable block, which changes the constant signal into a pulse as shown in Figure 3.6. The trip signal is input to an OR gate and then to the circuit breaker logic. On the other hand, the same output of the monostable block will pass through the recloser logic and the output of this logic will act as a close signal as shown in Figure 3.8.



(a)



(b)

Figure 3.6. (a) Monostable block, (b) Output signal of the monostable block

Within the recloser logic, the close signal will wait for a specific delay time before attempting to reclose. The pulse signal will change the counter value and the output will go high and remain high as shown in Figure 3.7 (b). This signal will be delayed and will be changed from a constant signal into a pulse by the monostable element as shown in Figure 3.7 (c) and Figure 3.7 (d). This signal is the close signal which passes through an OR gate toward the circuit breaker logic.

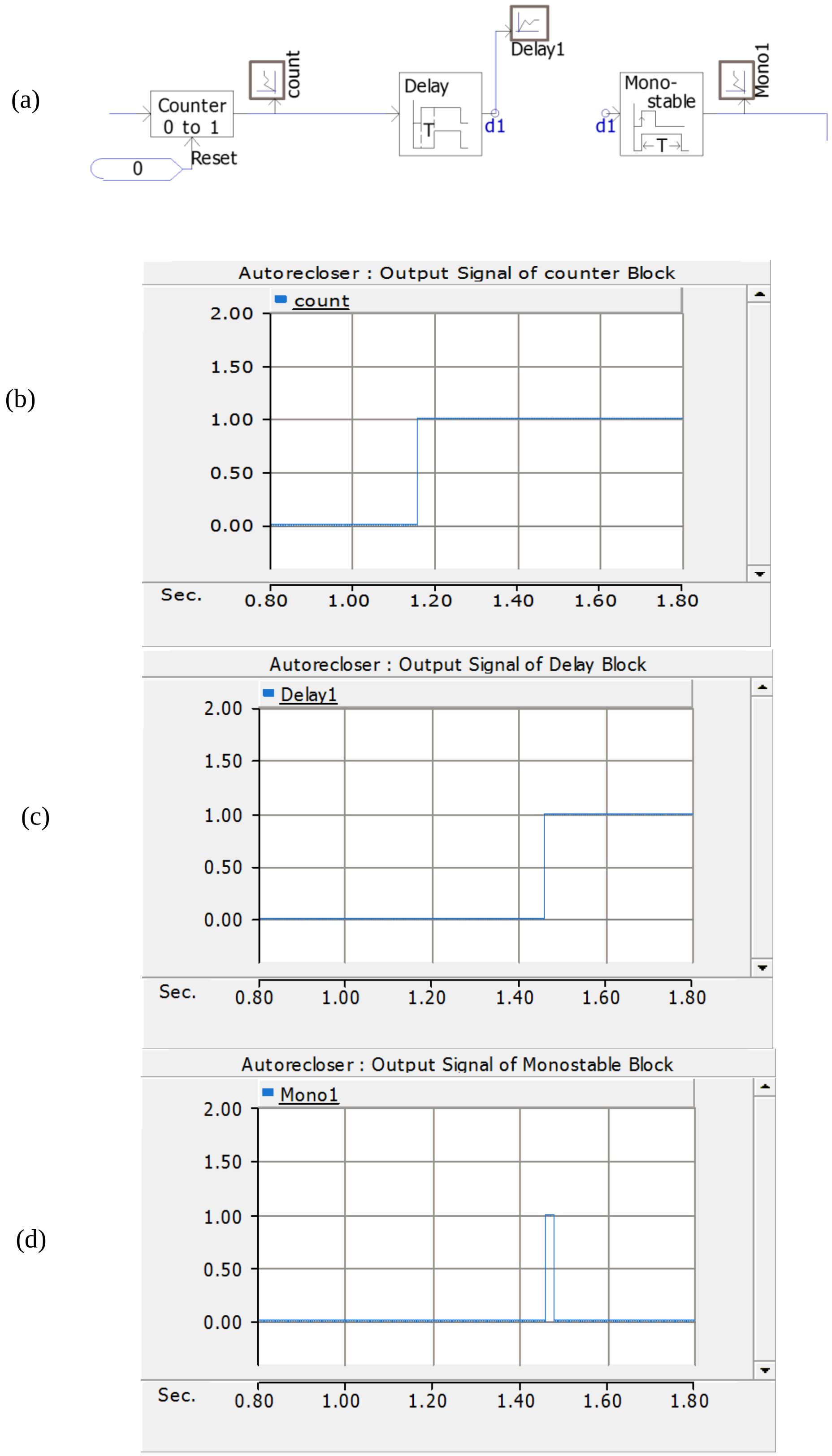


Figure 3.7. (a) Recloser logic, (b) Output signal of counter block, (c) Output signal of delay block, (d) Output signal of monostable block

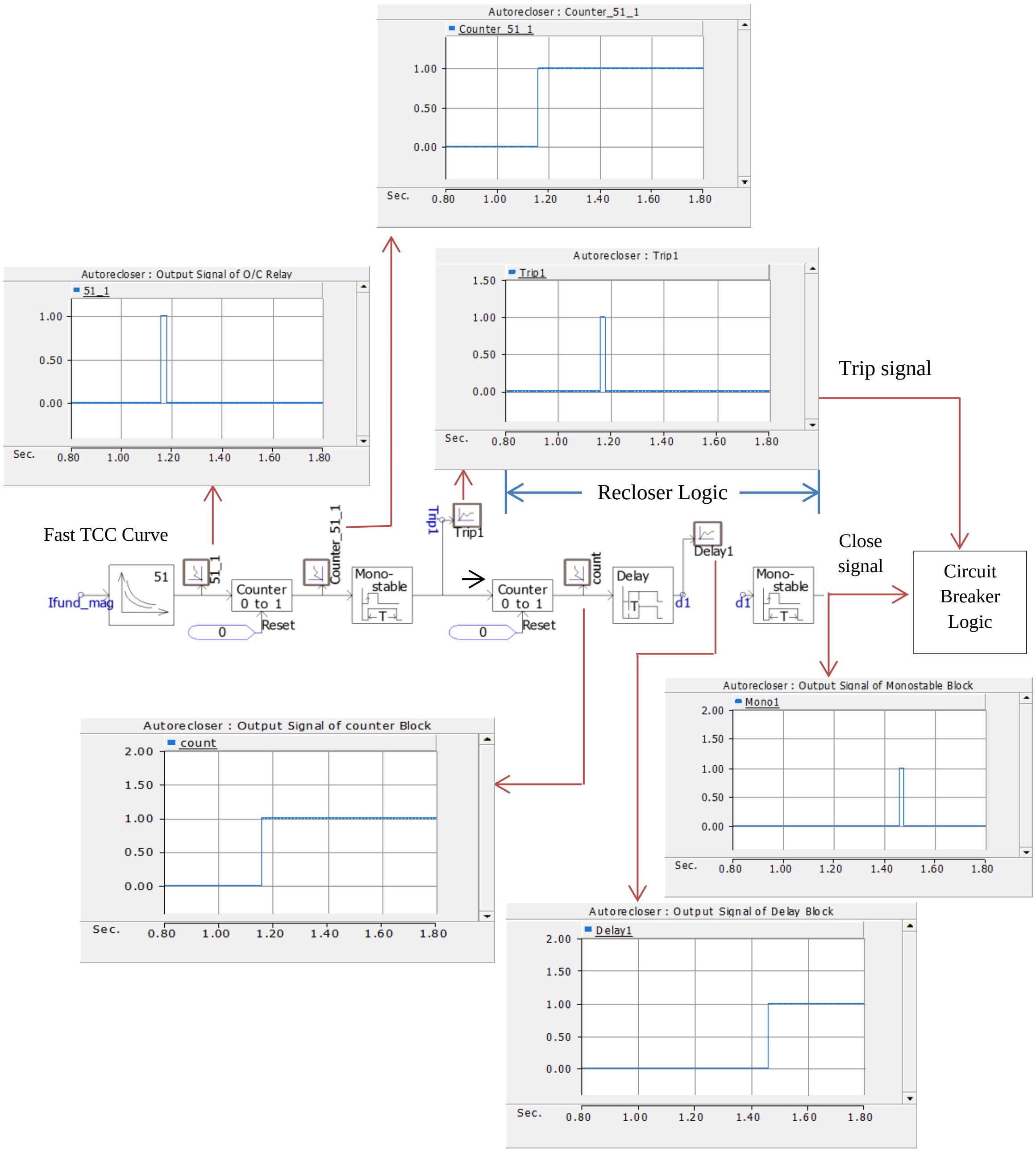


Figure 3.8. Output of each element of the fast operation

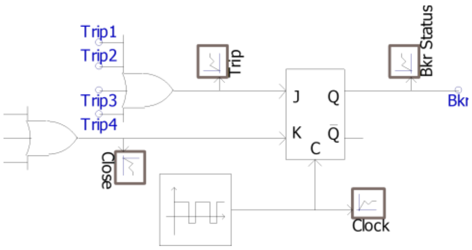


Figure 3.9. Circuit breaker logic

To control the operation of the circuit breaker model in PSCAD as a recloser, the states in Table 3.2 must be implemented. By default, the circuit breaker is closed in PSCAD. It will remain close as long as the input signal is 0 and it will be open when the input becomes 1 [31].

Table 3.2. Desired PSCAD Circuit Breaker Operations [31]

Trip	*Close*	*Breaker Status*
0	0	0
0	1	0
1	0	1
1	1	Not allowed

In order to achieve the desired operation in Table 3.2, the J-K flip-flop block must be used. Table 3.3 shows the truth table of the J-K flip –flop. According to [31], the circuit breaker is closed under normal operation conditions and both signals, Trip and Close, are 0. The flip-flop will keep it in the closed state in this case. During fault condition, the TRIP signal will be send to open the breaker. TRIP and CLOSE signals are low during the reclosing interval which keeps the breaker on open state. Then the CLOSE signal will be asserted, after a delay time, and the breaker will be back to the closed state.

Table 3.3. J-K Flip-Flop Truth (or true) Table Implementation [31]

J (TRIP)	*K (CLOSE)*	*Q (Breaker Status)*	$\bar{Q}$	*Description*
0	0	Q	$\bar{Q}$	Hold
0	1	0	1	Reset
1	0	1	0	Set
1	1	$\bar{Q}$	Q	Toggle (not allowed)

Up to this point, the recloser sequence of the first fast operation has been achieved. The operation of the other recloser sequences will be the same except for the last recloser sequence, the second delayed operation, where the close signal will not be sent to the circuit breaker logic to maintain the recloser opened (locked-out).

The second fast operation and the remaining recloser operations will not be activated until the two-selector control switch at each stage is activated. The output of the FFT is connected to selection B. The switch is set to selection A until a control signal from the delay element is received as shown in Figure 3.10.

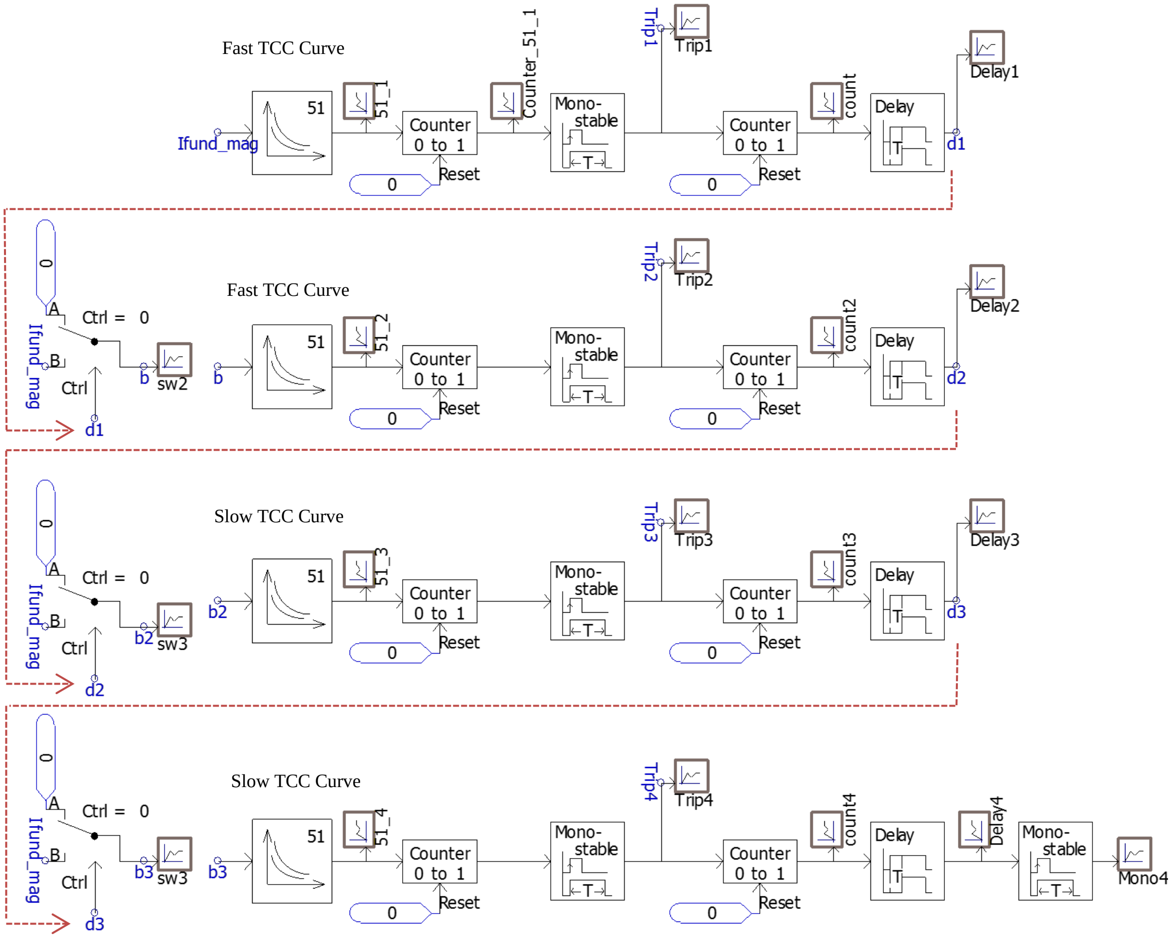


Figure 3.10. Activating of a two-selector control switches

3.2 MODEL VALIDATION

In order to confirm the functionality of the designed recloser model, the model is deployed to a simple single-phase distribution system. The one-line diagram of the system is shown in Figure 3.11 and the PSCAD model of the simulated distribution system is shown in Figure 3.12. The system consists of a feeder connected to an ideal source that feeds a load. The feeder is protected using a recloser. The test system is selected to be small in order to limit the number of variables.

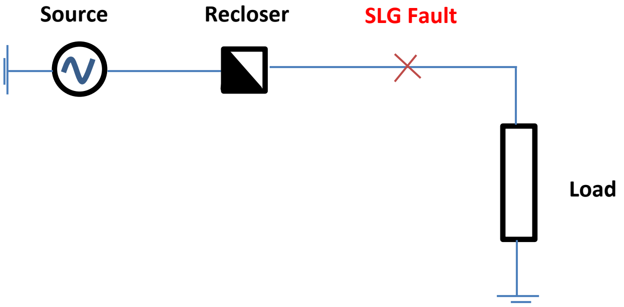


Figure 3.11. One-line diagram of a simple distribution circuit model

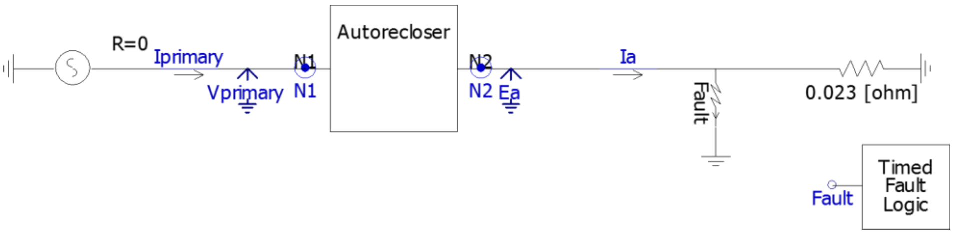


Figure 3.12. Simulated distribution system in PSCAD

3.3 EXPECTED AND SIMULATION RESULTS

This part shows the results from the simulations compared to expected results in order to confirm the efficacy of the recloser model. Since the test system is a simple radial distribution system, a single line to ground fault is applied. A series of test cases with temporary and permanent faults being applied to the considered distribution system are presented in Table 3.4.

Table 3.4. Fault cases considered in simulation study

Case No.	***Fault Location***	***Fault Nature***	***Fault Time (s)***	***Fault duration (s)***
1	Load side	Temporary, SLG	1	0.3
2	Load side	Temporary, SLG	1	0.75
3	Load side	Permanent, SLG	1	Permanent Fault

3.3.1 Case 1: Temporary SLG Fault between the Recloser and the Load (One Fast Operation).

The recloser model is simulated for a temporary fault between the recloser and the load. The fault starts at t=1s and is self-cleared at 1.3s. The recloser is pre-programmed to operate in fuse saving mode (2-fast, 2-delayed operations).

Table 3.5. Parameter values of the test system

Parameters	*Value*
Line–line Input voltage (ideal source)	1 kV
Power frequency	60 Hz
Load R	0.023 Ω
Current Transformer Ratio (CTR)	300/5 A
Fault Nature	Temporary, Bolted SLG

Table 3.6. Recloser setting

Type of characteristics	Extremely inverse	
Type of Curve - Standard	IEEE Std. C37.112	
Curve Type	Pickup Current (I_{pickup})	Time Dial Setting (TD)
Fast Curve	1.0	0.05
Slow Curve	1.0	0.1

Table 3.7. Recloser Interval Setting

Reclose Interval	*Duration (s)*
First	0.3
Second	0.5
Third	0.5

3.3.1.1 Expected results for case 1. The recloser will act immediately and will remain open till the end of first reclose interval. Because the fault is self-cleared (at t=1.3s) before the end of the first reclose interval, the supply will be restored in this case after one reclosing shot as shown in Figure 3.13.

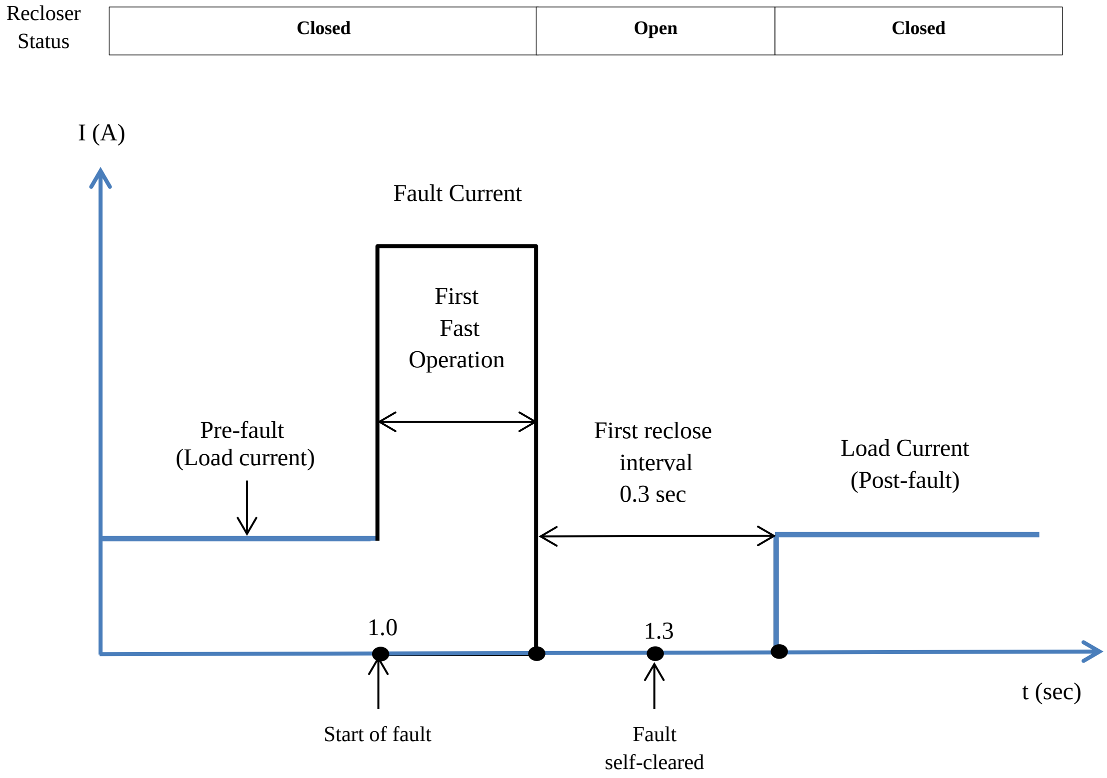


Figure 3.13. Expected recloser status, recloser current for one fast operation

The operation time of the inverse-time overcurrent relay is defined mathematically according to IEEE Std C37.112-1996 by the following expression [11][32]:

$$t(I) = \frac{TD * A}{M^P - 1} + B \tag{3.1}$$

where

$t(I)$	relay operating time in seconds
M	is the $\frac{I_{input}}{I_{pickup}}$ (I_{pickup} is the pickup current selected)
TD	time dial setting.
A, B, P	constants to provide selected curve characteristics

The values of A, B and P are displayed in Table 4.8. The recloser setting values are shown in Table 3.6.

Table 3.8. IEEE Std C37.112-1996 constants for standard characteristics [32]

Curve characteristics	*A*	*B*	*P*
Moderately inverse	0.0515	0.1140	0.02
Very inverse	19.61	0.491	2.0
Extremely inverse	28.2	0.1217	2.0

Equation 3.1 along with the constants on Table 3.8 defines the curve near the middle of the time dial range [32] as shown in Figure 3.14. “The standard allows relays to have tripping times within 15% of the curves”[11]. Therefore any results from the simulation between 0.85 t (I) and 1.15 t (I) will be accepted.

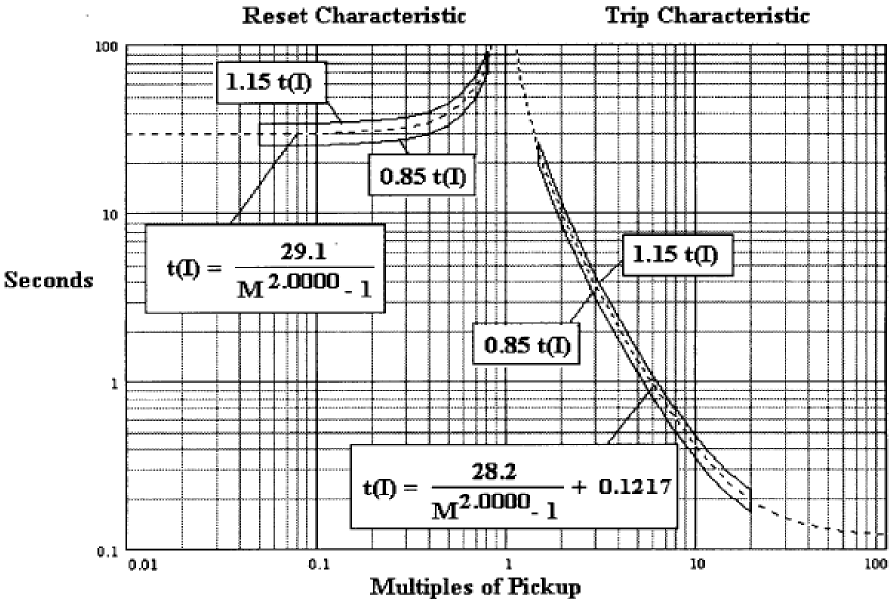


Figure 3.14. Standard extremely inverse time-current characteristic with standard conformance band near the middle of the time dial range [32]

3.3.1.2 Simulation results for case 1. Figures 3.15 – Figure 3.18 show the outputs from the PSCAD simulation.

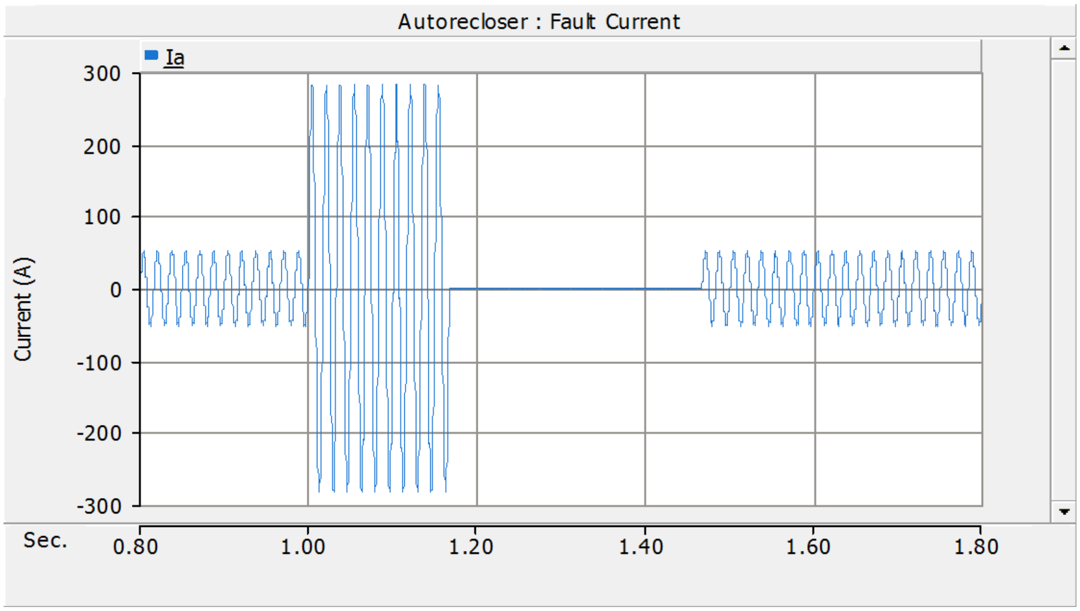


Figure 3.15. Simulated current waveform between the recloser and fault location for one fast operation

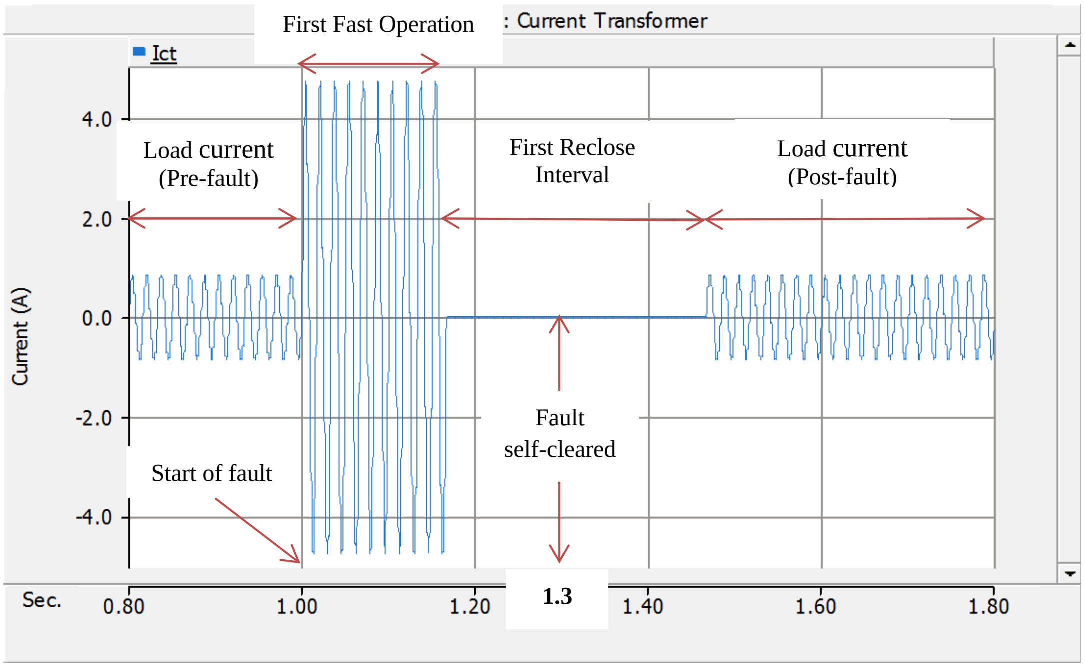


Figure 3.16. Simulated current waveform seen by the time-inverse overcurrent relay for one fast operation

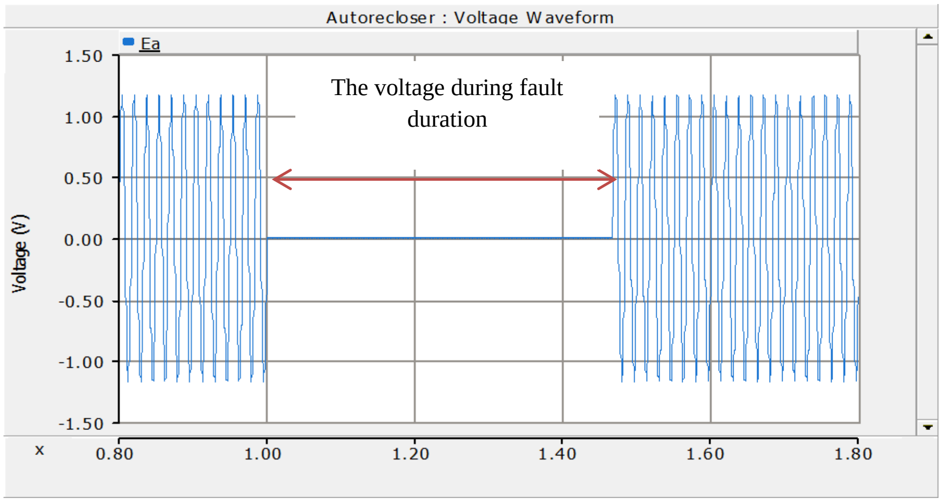


Figure 3.17. Voltage waveform between the recloser and fault location for one fast operation

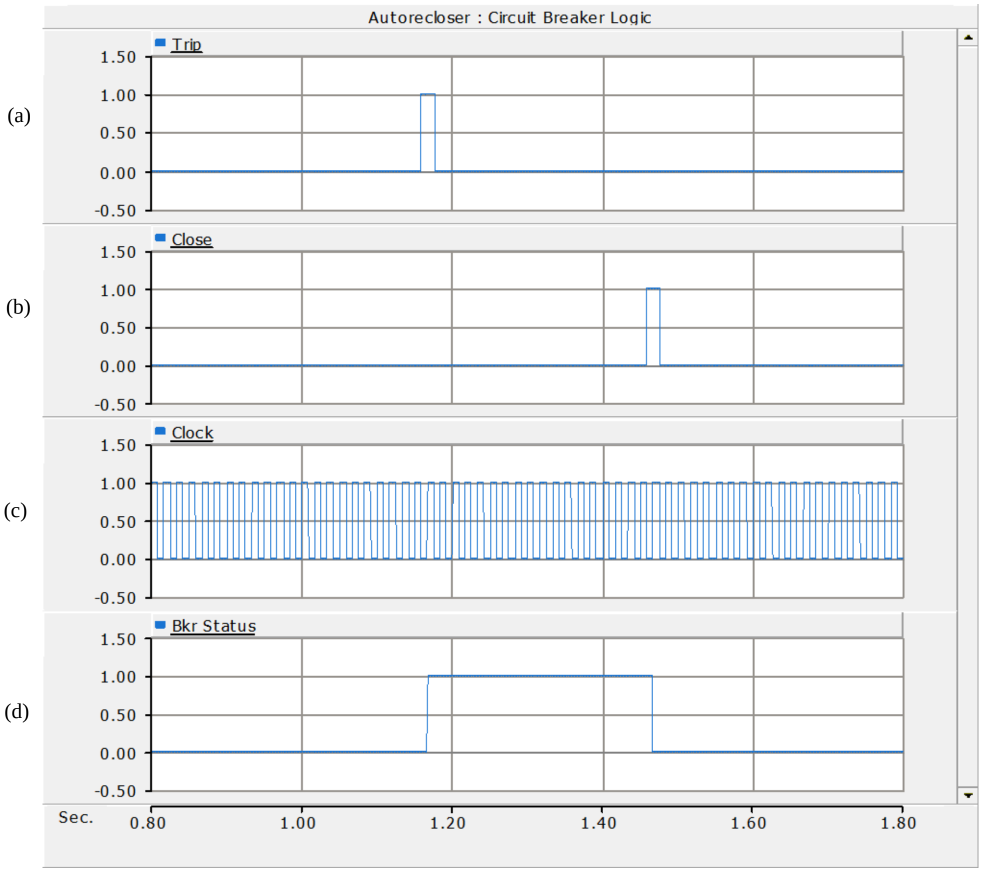


Figure 3.18. (a) Trip signal from the overcurrent relay to the breaker. (b) Close signal from the control circuit to the breaker. (c) Clock signal used to activate a flip-flop transition. (d) Breaker status

By using Equation 3.1 and the values in Table 3.6 and Table 3.8, we can calculate the theoretical operating time value for the first fast operation (since the fault self-clears after the first fast operation during the first reclose interval in this case). The simulation and theoretical values are presented in Table 3.9.

Table 3.9. Expected and simulation results for one fast operation, case 1

	Relay operating time in seconds, t(I)		
	Theoretical		*Simulation value*
Curve Type	t(I)	Tripping time range 0.85t(I) – 1.15t(I)	t(I)
Fast Curve	0.188	0.1598 – 0.2162	0.1765

As shown from Table 3.9 above, the simulated value of t(I) is within the tripping time range which means that the simulation results are good. From Figure 3.19 and Figure 3.20, we can observe that the recloser model operates as expected. This means that the control circuit is performing well and this validates the control circuit of the recloser model.

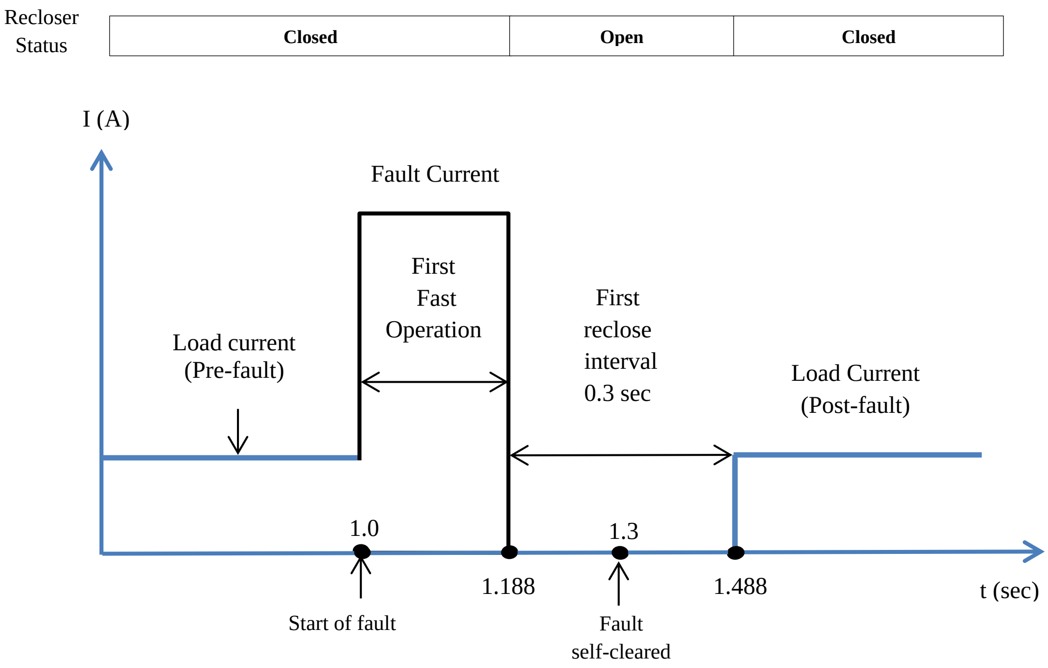


Figure 3.19. Expected recloser status, recloser current profile and sequence of timings (one fast operation)

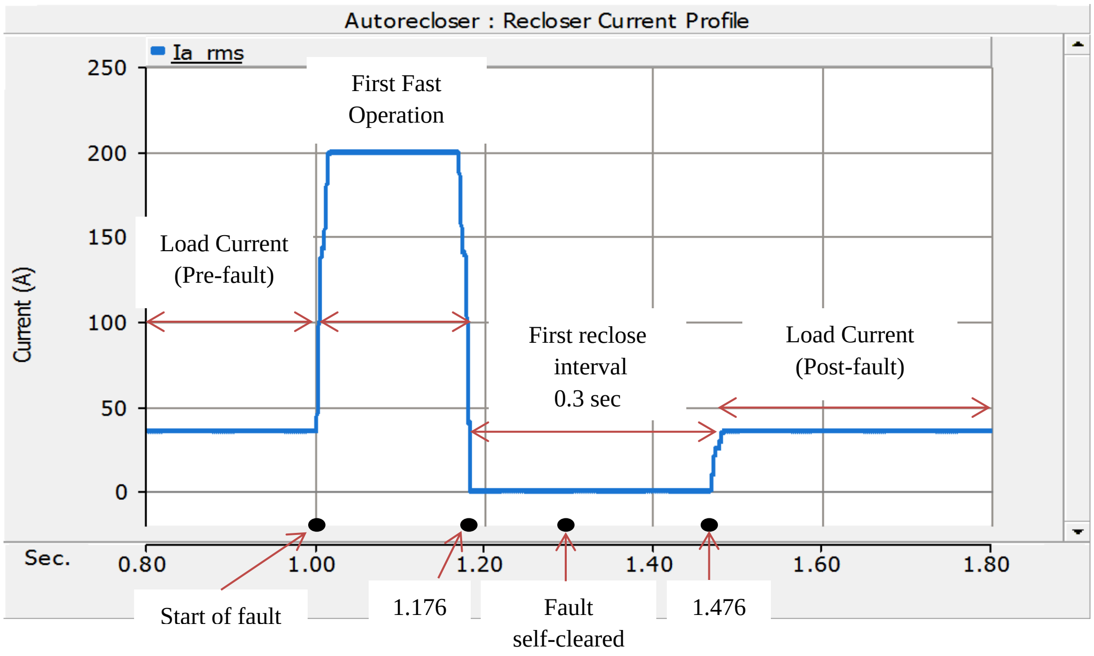


Figure 3.20. Simulated recloser current profile and sequence of timings for one fast operation

3.3.2 Case 2: Temporary Fault between the Recloser and the Load (Two Fast Operations).

The recloser model is simulated for a temporary fault between the recloser and the load to confirm the operation of the control circuit of the recloser model in case of temporary fault which is self-cleared during the second reclose interval. The fault starts at t= 1s and is self-cleared at 1.75s (fault duration is 0.75s). The recloser is pre-programmed to operate in fuse saving mode (2-fast, 2-delayed operations). The recloser setting and system parameters values are shown in Table 3.5 - Table 3.7.

3.3.2.1 Expected results for case 2.

The fault current will pass through the recloser; it will trip and open the circuit to clear the fault. Since the fault still persists, the overcurrent relay will detect the fault current and starts to resend a trip signal to the breaker. Once the breaker opens, the current seen by the recloser immediately drops to zero. Because the fault is self-cleared (at t=1.75s.) before the end of the second reclose interval, the supply will be restored by the end of the second reclose interval as shown in Figure 3.21.

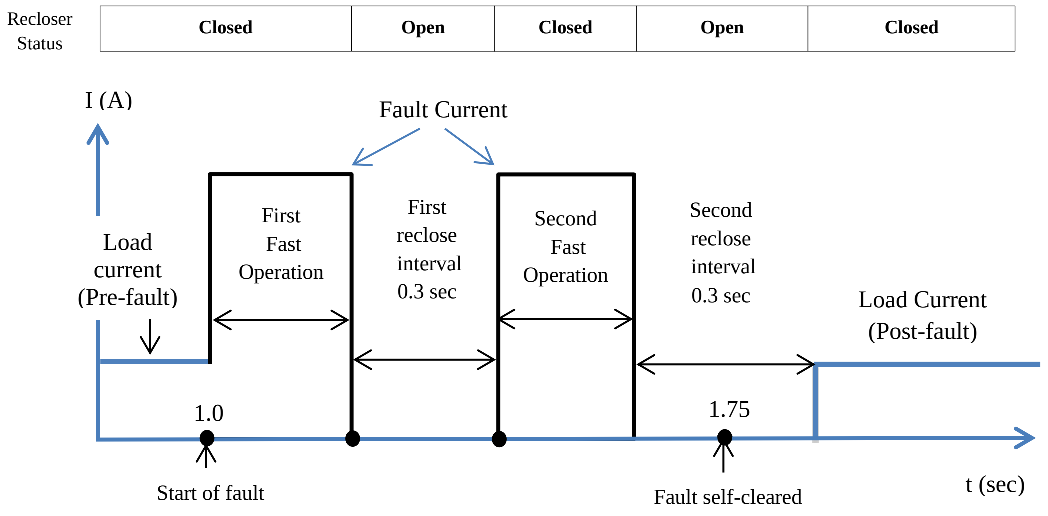


Figure 3.21. Expected recloser status, recloser current for two fast operation

3.3.2.2 Simulation results for case 2. Figure 3.22 – Figure 3.25 shows the outputs from the PSCAD simulation.

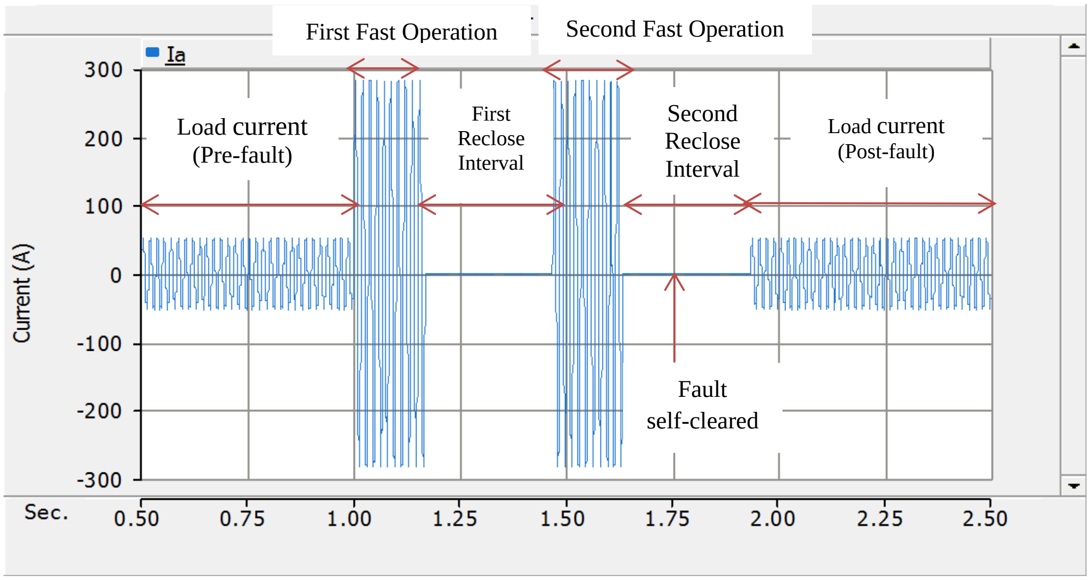


Figure 3.22. Simulated current waveform between the recloser and fault location for two fast operations

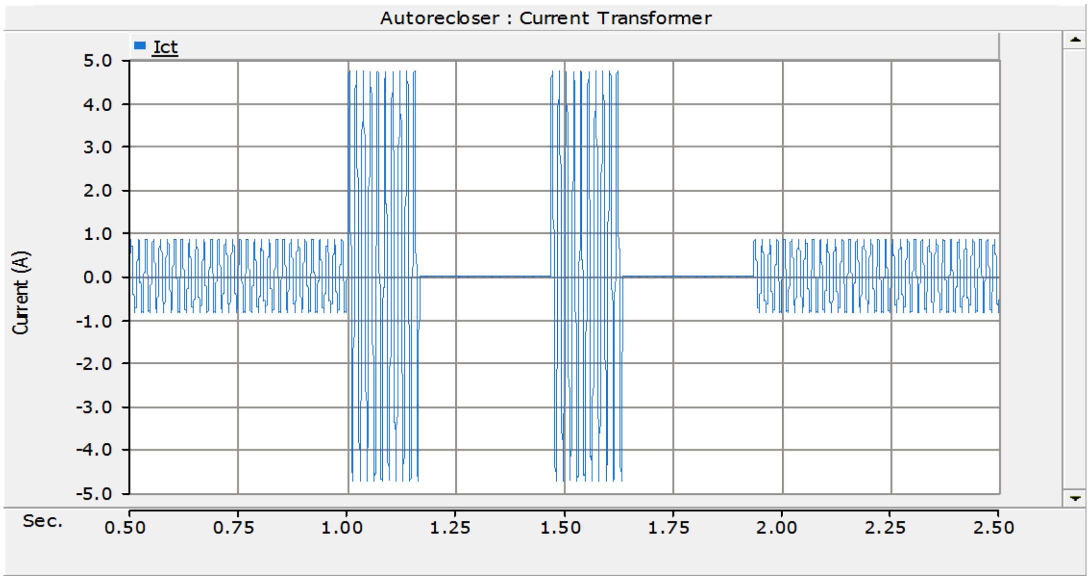


Figure 3.23. Simulated current waveform seen by the time-inverse overcurrent relay for two fast operations

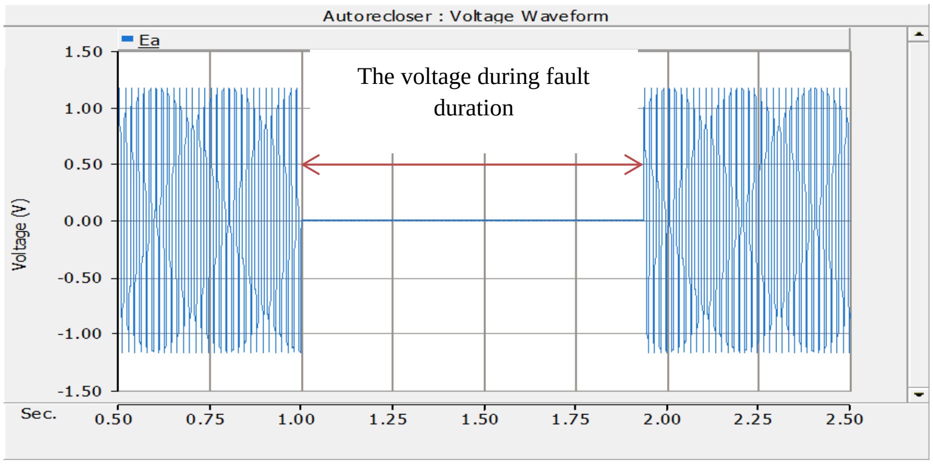


Figure 3.24. Voltage waveform between the recloser and fault location for two fast operations

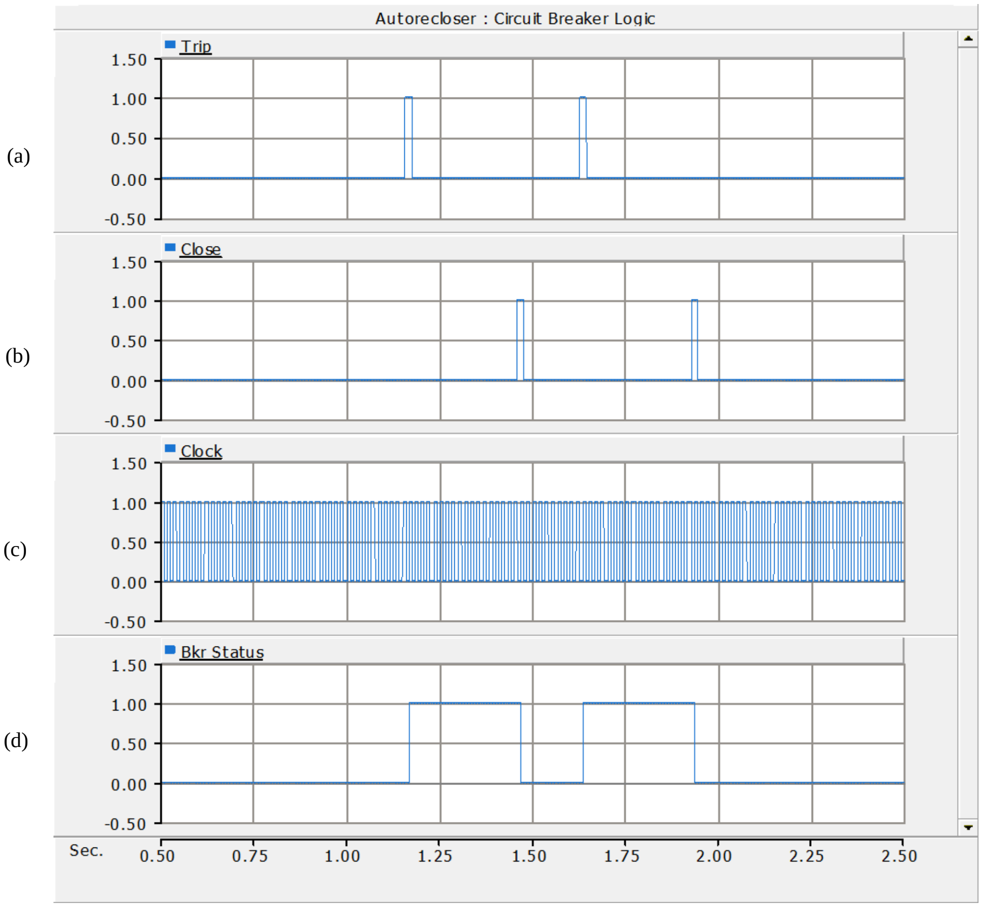


Figure 3.25. Trip signal from the overcurrent relay to the breaker. (b) Close signal from the control circuit to the breaker. (c) Clock signal used to activate a flip-flop transition. (d) Breaker status

The expected operating time for the first and second fast operations are calculated as in case 1. The calculated and simulated values are presented in Table 3.10. The recloser setting values for the first and second fast operations are the same as shown in Table 3.6.

Table 3.10. Expected and simulation results for two fast operations, case 2

	Relay operating time in seconds, t(I)		
	Theoretical		*Simulation value*
Curve Type	t(I)	Tripping time range 0.85t(I) – 1.15t(I)	t(I)
Fast Curve	0.188	0.1598 – 0.2162	0.1765

As shown from Table 3.10 above, the simulated value of t(I) is within the tripping time range which means that the simulation results are good. From Figure 3.26 and Figure 3.27, we can observe that the recloser model operates as expected.

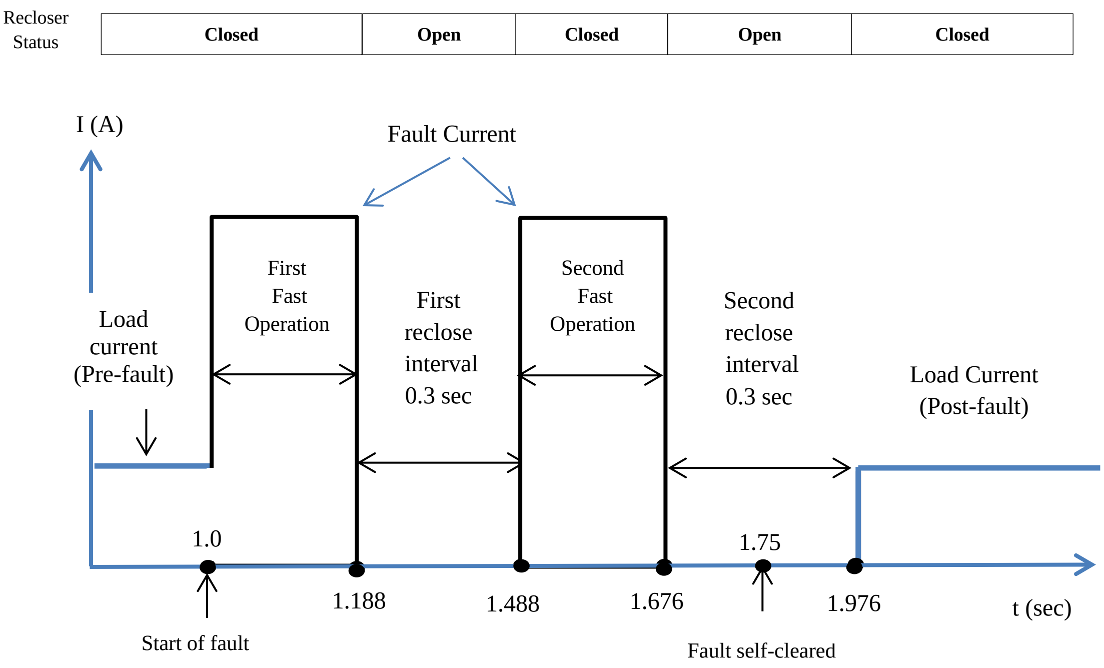


Figure 3.26. Expected recloser status, recloser current profile and sequence of timings for two fast operations

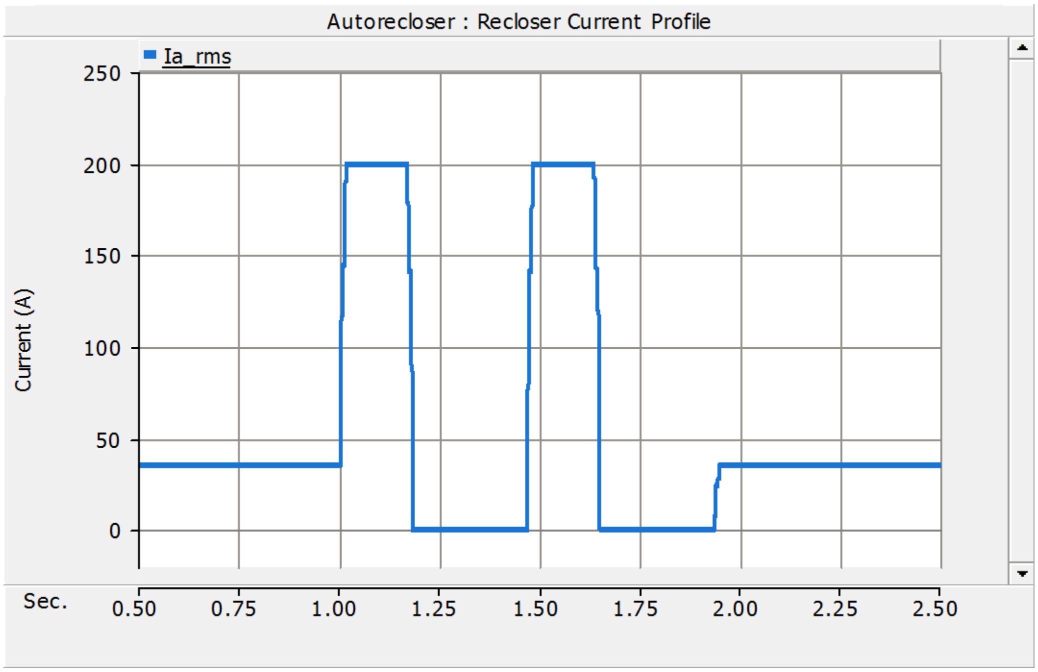


Figure 3.27. Simulated recloser current profile and sequence of timings for two fast operations

3.3.3 Case 3: Permanent Fault between the Recloser and the Load (2-Fast, 2-Delayed Operations). The recloser model is simulated for a permanent fault between the recloser and the load to confirm the operation of the control circuit of the recloser model. The fault starts at t= 1s. The recloser is pre-programmed to operate in fuse saving mode (2-fast, 2-delayed operations). The system parameters and recloser setting values are shown in Table 3.5 - Table 3.7. The second and third reclose intervals are 1s.

3.3.3.1 Expected results for case 3. In this case the recloser will open for four shots (2-fast and 2-delayed). Since the fault is permanent, after the fourth shot the recloser will be locked-out and the system will be de-energized. Figure 3.28 shows the expected recloser status and recloser current profile.

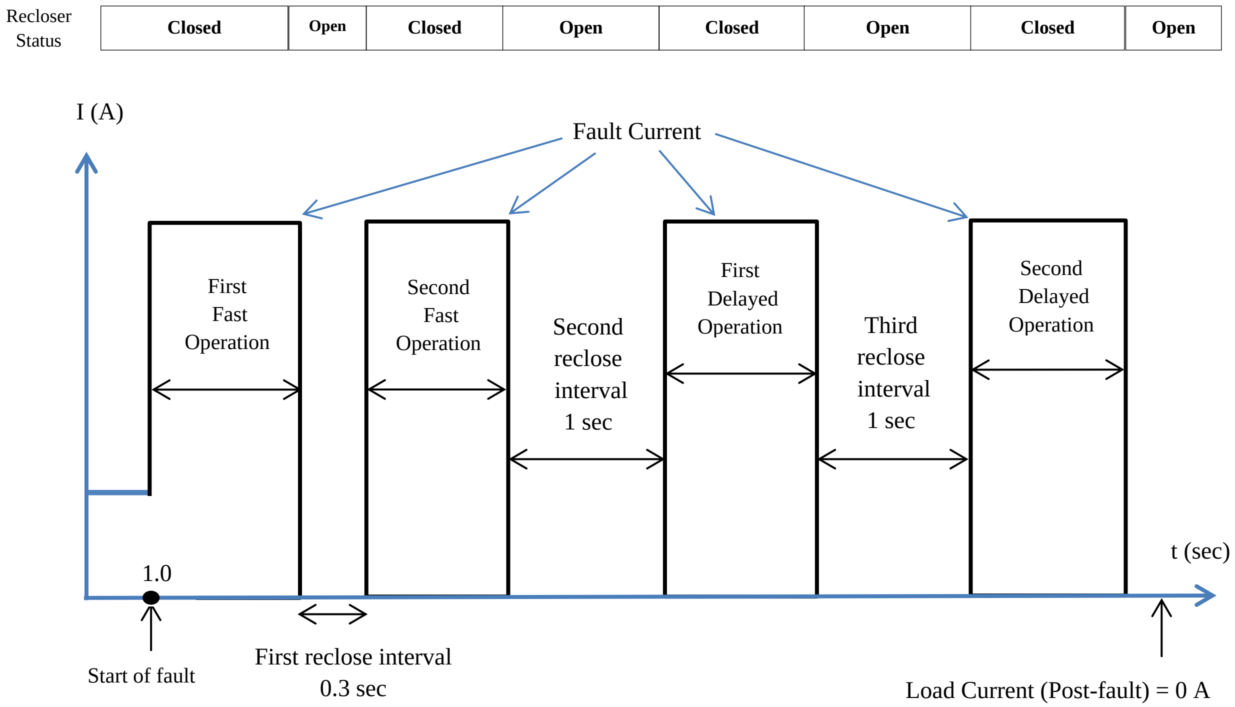


Figure 3.28. Expected recloser status, recloser current for 2-fast, 2-delayed operations

3.3.3.2 Simulation results for case 3.

Figure 3.29 – Figure 3.32 shows the outputs from the PSCAD simulation.

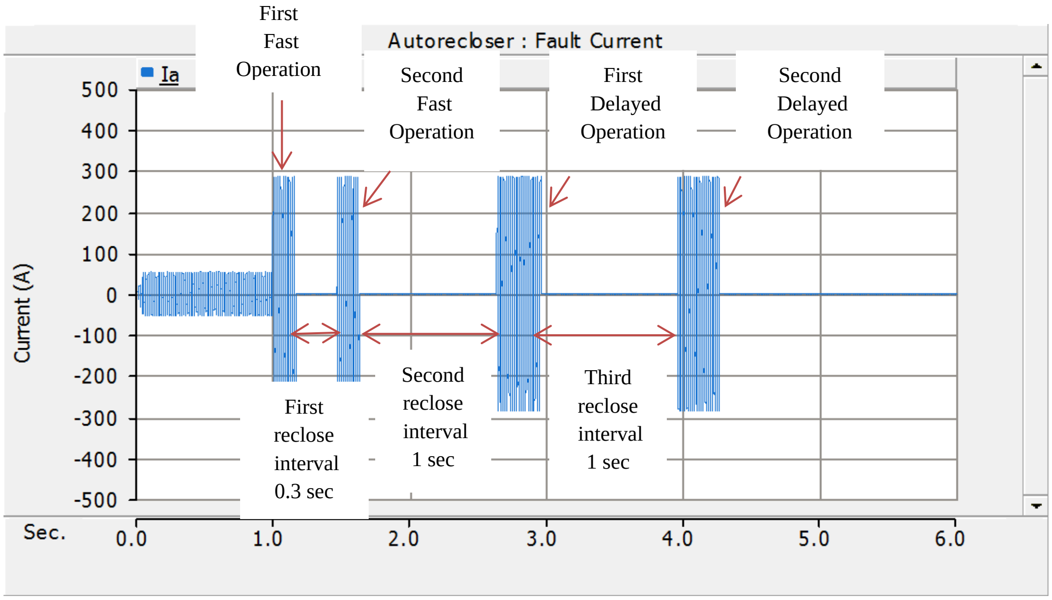


Figure 3.29. Simulated current waveform between the recloser and fault location for 2-fast, 2-delayed operations

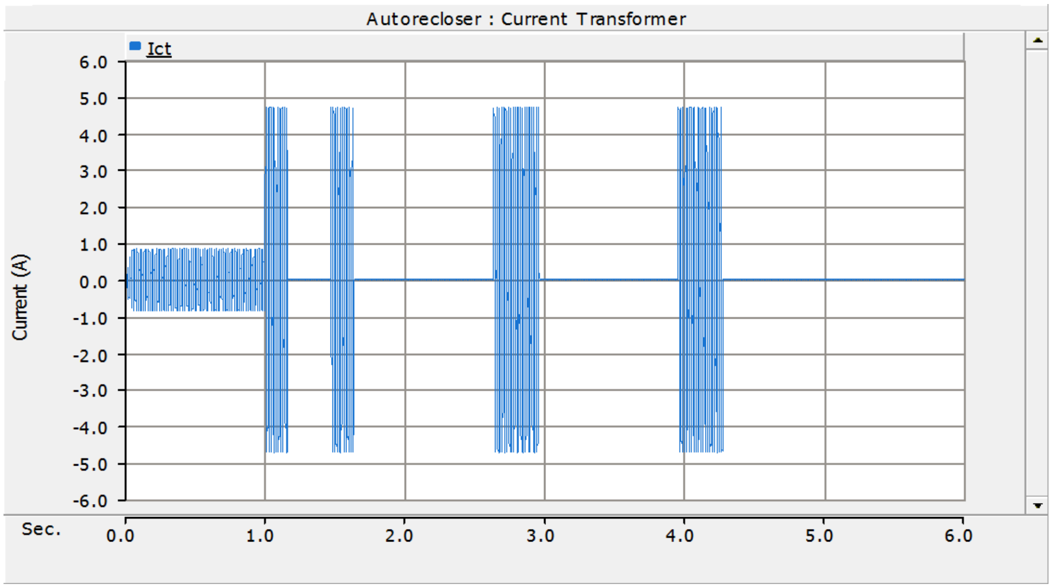


Figure 3.30. Simulated current waveform seen by the time-inverse overcurrent relay for 2-fast, 2-delayed operations

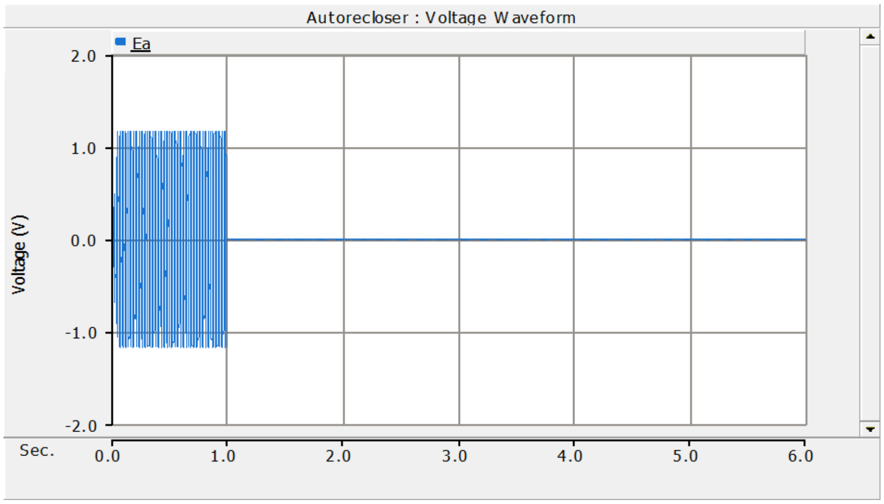


Figure 3.31. Voltage waveform between the recloser and fault location for 2-fast, 2-delayed operations

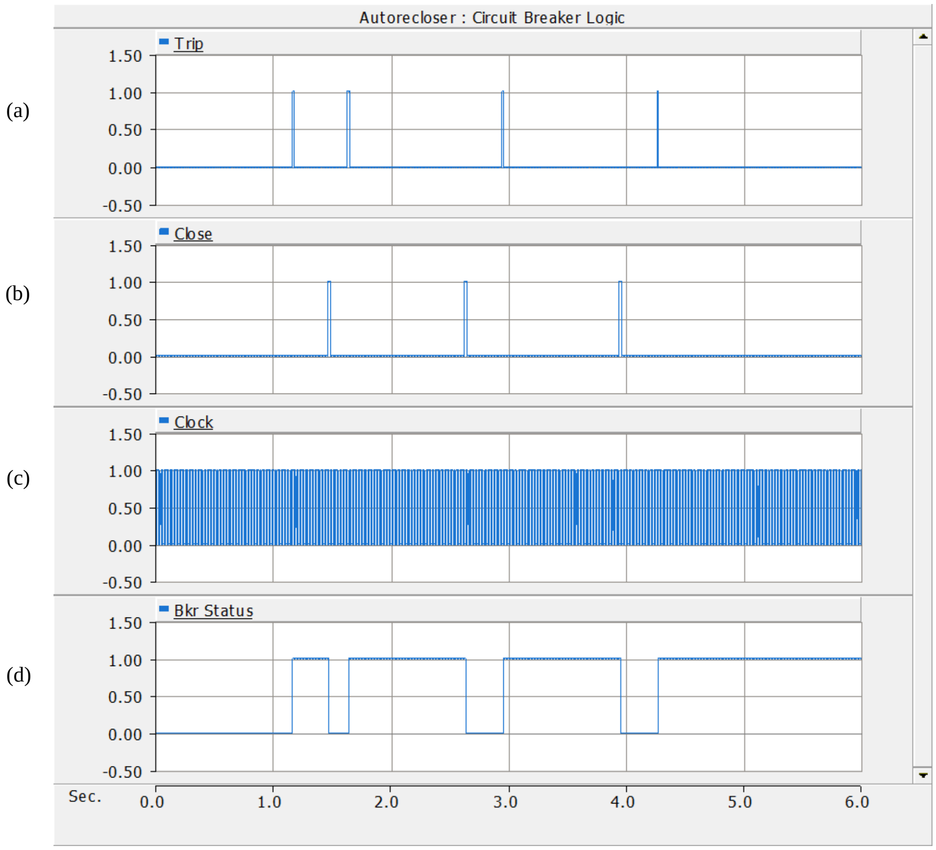


Figure 3.32. (a) Trip signal from the overcurrent relay to the breaker. (b) Close signal from the control circuit to the breaker. (c) Clock signal used to activate a flip-flop transition. (d) Breaker status

The expected operating time simulated values and presented in Table 3.11. The recloser setting values are same as shown in Table 3.6. The second and third reclose intervals are 1 sec.

Table 3.11. Expected and simulation results for 2-fast, 2-delayed operations

	Relay operating time in seconds t(I)		
	Theoretical		*Simulation value*
Curve Type	t(I)	Tripping time range 0.85t(I) – 1.15t(I)	t(I)
Fast Curve	0.1886	0.1603 – 0.2169	0.1765
Slow Curve	0.2554	0.2171 – 0.2937	0.2940

As shown from Table 3.11 above, the simulated value of t(I) is within the tripping time range which means that the simulation results are good. From Figure 3.33 and Figure 3.34, we can observe that the recloser model operates as expected.

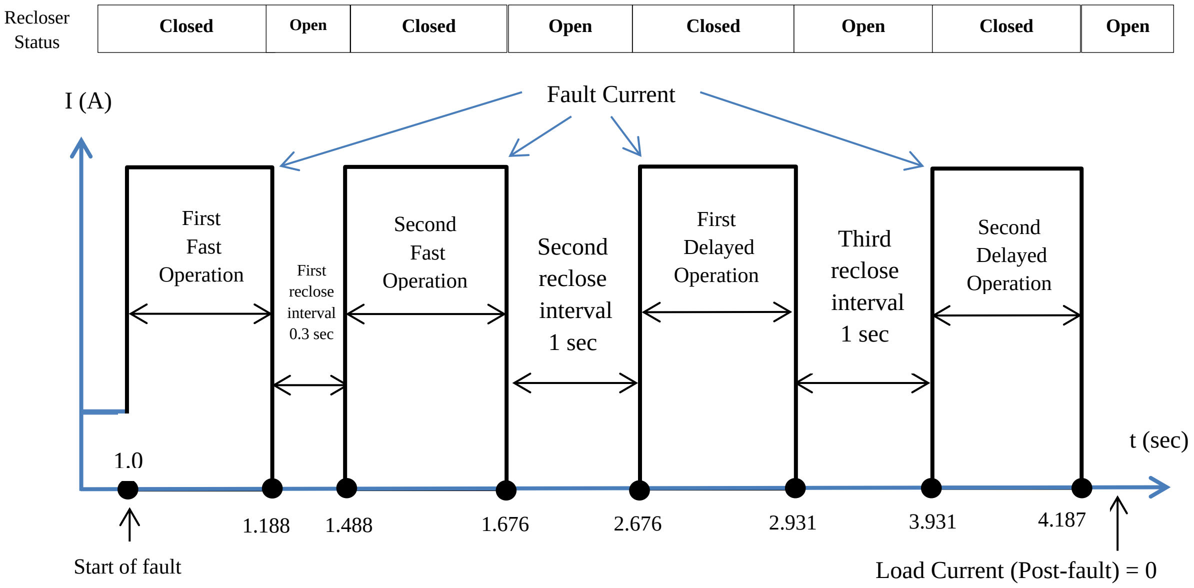


Figure 3. 33. Expected recloser status, recloser current and sequence of timings for 2-fast, 2-delayed operations

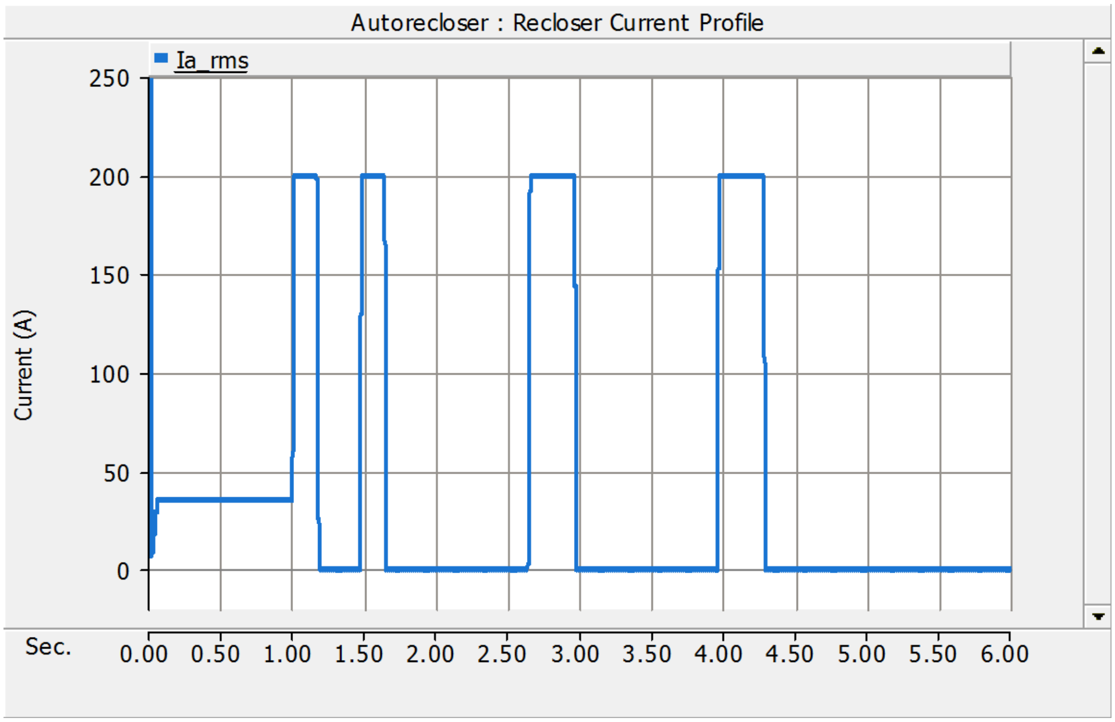


Figure 3.34. Simulated recloser, current profile and sequence of timings for 2-fast, 2-delayed operations

3.4 SUMMARY

The objective of this section is to design a recloser model in PSCAD since PSCAD®/EMTDC™ does not have a recloser block in its library. The model was validated by deploying it in a simple distribution system and different test cases are presented. Simulations were run for different cases in order to confirm the control circuit logic of the recloser model. The results of the simulations were compared with the theoretical results. We can observe that the recloser model operates as expected.

4. SYSTEM STUDY AND SIMULATION RESULTS

The objective of this section is to study the behavior of a solid-state transformer (SST) under the operation of the recloser. The autorecloser was designed and tested as shown in section 3. The same recloser model will be used once along with the traditional line frequency transformer (LFT) and again with the SST in PSCAD®/EMTDC™ software. A comparison will be presented between these two types of transformers and their behaviors during operation of protective devices. This study is restricted to single-phase SSTs, since topologies for three-phase SSTs are still in the development stage [8].

4.1. TEST SYSTEM

In order to study the behavior of the solid-state transformer (SST), the recloser and SST models are deployed in a simple single-phase distribution system. The one-line diagram of the system is shown in Figure 4.1 and the PSCAD models of the simulated distribution system are shown in Figure 4.2 and Figure 4.3.

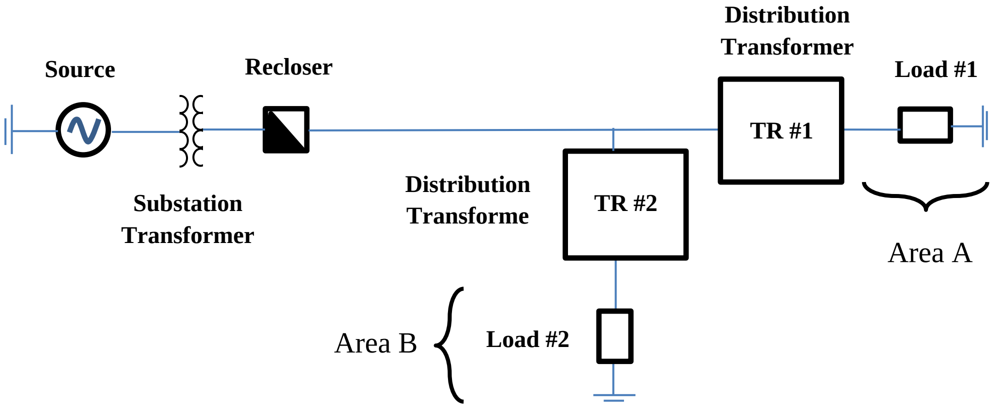


Figure 4.1. One-line diagram of the test distribution circuit

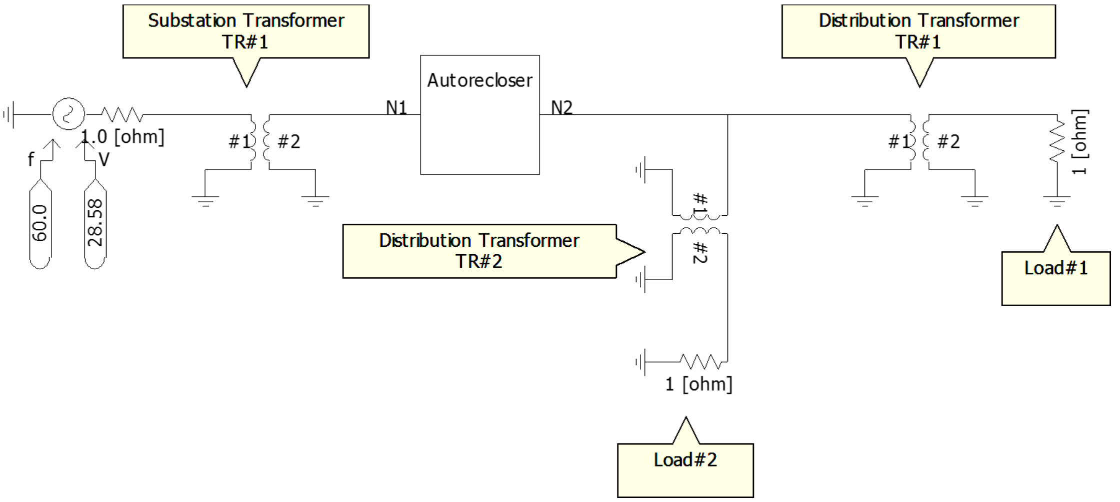


Figure 4.2. Simulated distribution system (System#1) using traditional line frequency transformers (LFT) in PSCAD

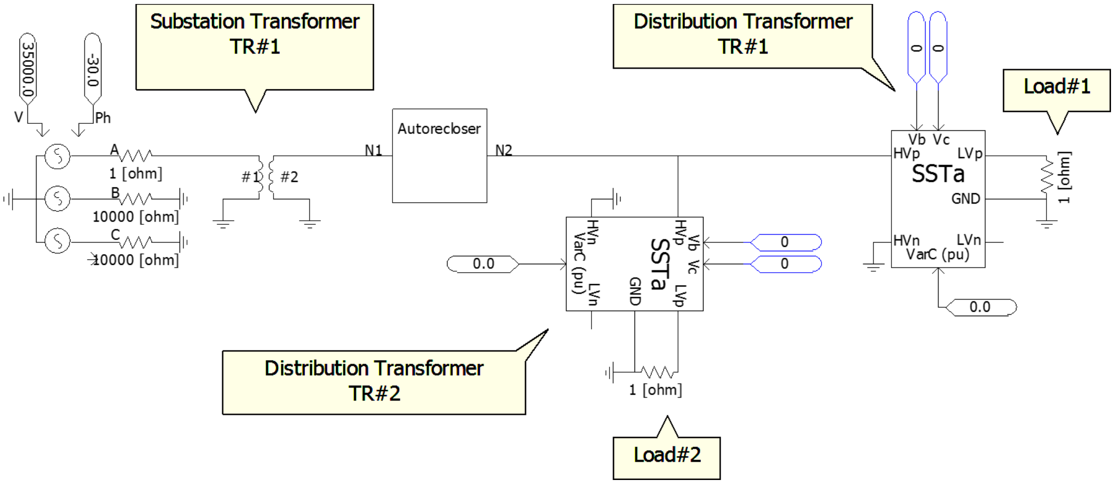


Figure 4.3. Simulated distribution system (System#2) using Solid State Transformers (SST) in PSCAD

As shown in Figure 4.1, the system is comprised of a feeder connected to an ideal source through a traditional line frequency transformer (LFT). The transformer supplies two single-phase resistive loads. Load#1 represents the customers at Area A and Load#2 represents the customers at Area B. The parameter values used for simulations have been shown in Table 4.1 and Table 4.2.

Table 4.1. Parameter values of the test system

Parameters	*Value*
Line–Ground Input voltage (ideal source)	20.21 kV
Substation Transformer, TR#1	20.21/ 7.2 kV, 10 MVA
Distribution Transformers, TR#1 & 2	7.2 / 0.12 kV, 25 kVA
Power frequency	60 Hz
Loads, R	1 Ω
Current Transformer Ratio (CTR)	1200/5 A

Table 4.2. Recloser setting values

Type of characteristics	Extremely inverse	
Type of Curve - Standard	IEEE Std. C37.112	
Curve Type	Pickup Current (I_{pickup})	Time Dial Setting (TD)
Fast Curve	2.0	0.3
Slow Curve	5.0	0.5

4.2 SIMULATION RESULTS

In this part, the results from the simulations will be presented. Since the test system is a simple radial distribution system, a single line to ground fault is applied to the locations as shown in Table 4.3 and Figure 4.4. The results of several test cases with temporary and permanent faults being applied to the considered distribution system are presented below.

Table 4.3. Fault cases considered in simulation study

Case No.	*Fault Location*	*Fault Nature*	*Fault Time (s)*	*Fault duration (s)*
1	F1	Permanent, SLG	1	Permanent Fault
2	F1	Temporary, SLG	1	0.2
3	F2	Permanent, SLG	1	Permanent Fault
4	F3	Permanent, SLG	1	Permanent Fault

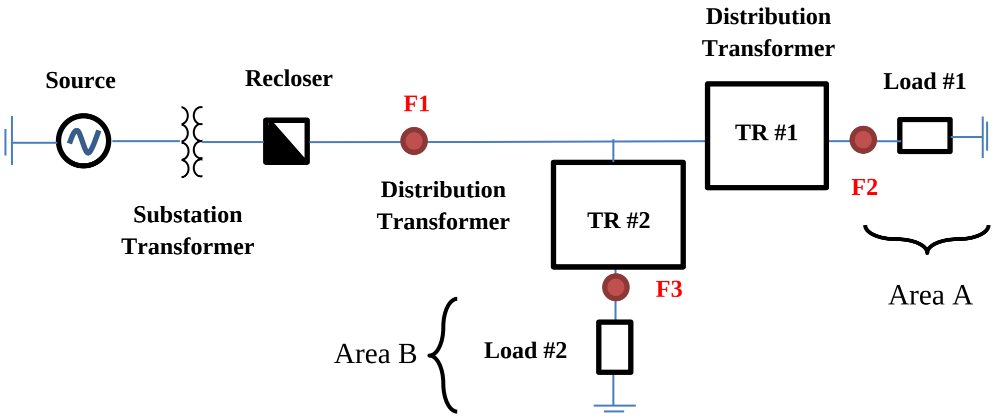


Figure 4.4. Fault locations on the test distribution circuit

4.2.1 Case 1: Permanent Fault on the Main Feeder (2-Fast, 2-Delayed Operations). In this case we describe a permanent phase-to-ground fault on a solidly grounded system which may have been caused by touching of a tree branch to phase A and the ground. The fault occurs at t=1s and since the fault is permanent, the recloser will open for three shots and after the fourth shot the recloser will be locked-out and the system will de-energized. Figure 4.6 – Figure 4.11 shows the outputs of the simulation. Again, System#1 means the system in Figure 4.2 and System#2 means the system in Figure 4.3.

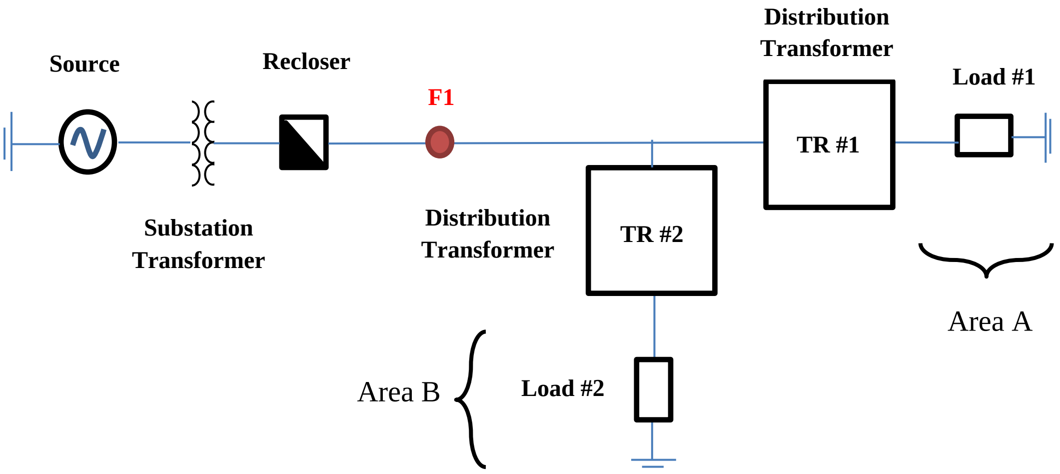


Figure 4.5. The test system for case 1

At the moment of line-to-ground fault, the current passing through the recloser will be many times the load current. This huge amount of fault current will activate the recloser. Since the fault is permanent, the recloser will operate for four times, two-fast and two-slow operations, then it will be locked-out and the system gets de-energized as shown in Figure 4.6 and Figure 4.7.

One of the most important features of the SST, as discussed in [5], is shown in Figure 4.7 and Figure 4.8. We can observe that at the moment of the fault (t=1s), the customers in Area A&B in System#1 will be out of service immediately. On the other hand, the customers in the same areas in System#2, who get their supply through SSTs, will continue receiving power for few seconds. That is referred to the SST capability to maintain output power for few cycles due to the energy stored in the DC link capacitor. This feature is important especially if we have two or more circuits interconnected by using a proper bus arrangements and protection scheme. So the system will have enough time to transfer the loads to a healthy bus in order to continue feeding the loads.

Figure 4.10 and Figure 4.11 demonstrate the SST response under a permanent fault. During the fault, the high voltage DC bus decreases from 3.8 kV up to 2.8 kV before the internal protection unit inside the SST switches it off. The low voltage DC bus is stable around 400 V during the fault. Figure 4.11 shows the active and reactive power into the SST during the fault.

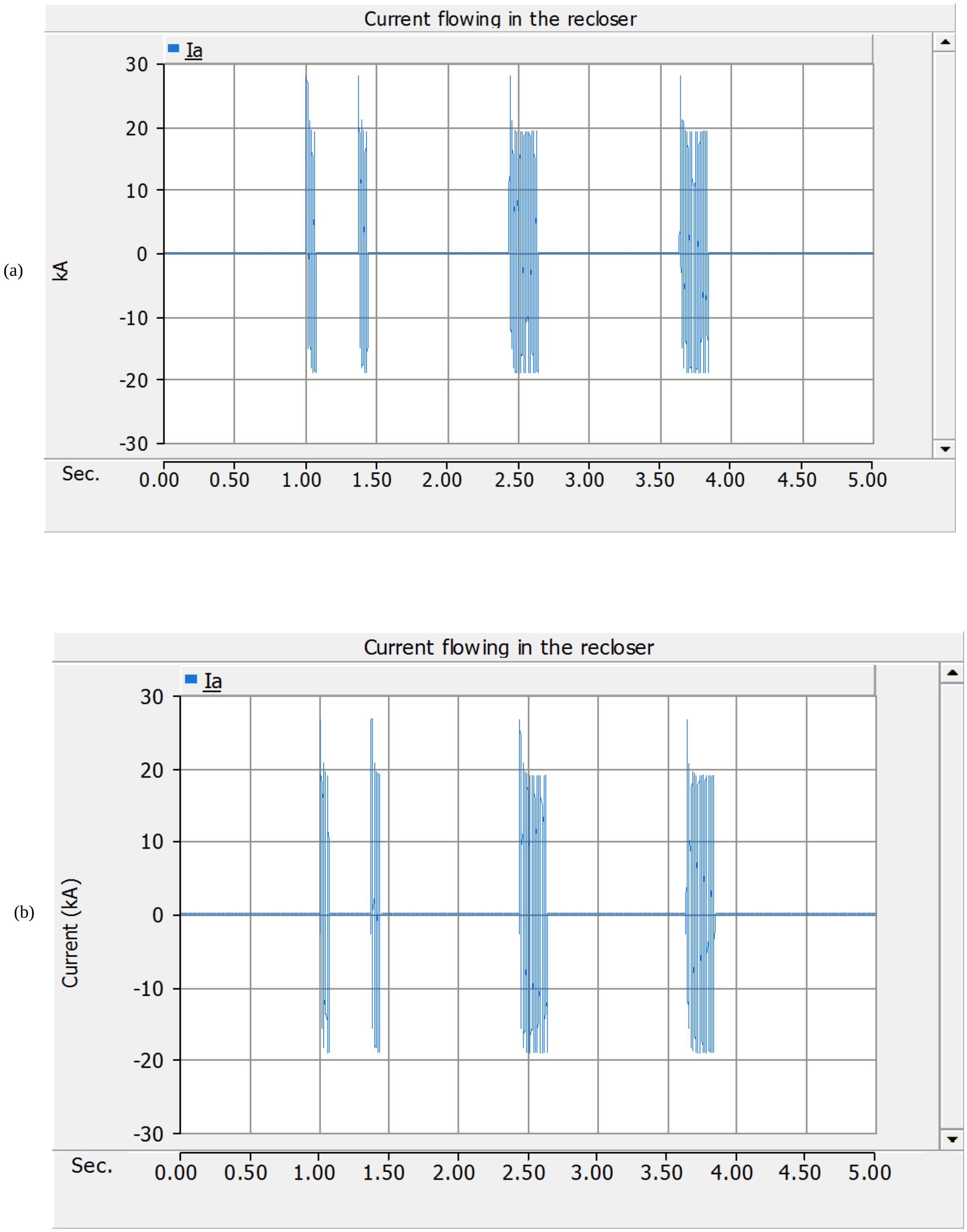


Figure 4.6. Current waveform waveform seen by the recloser: (a) System#1(LFT), (b) System#2 (SST)

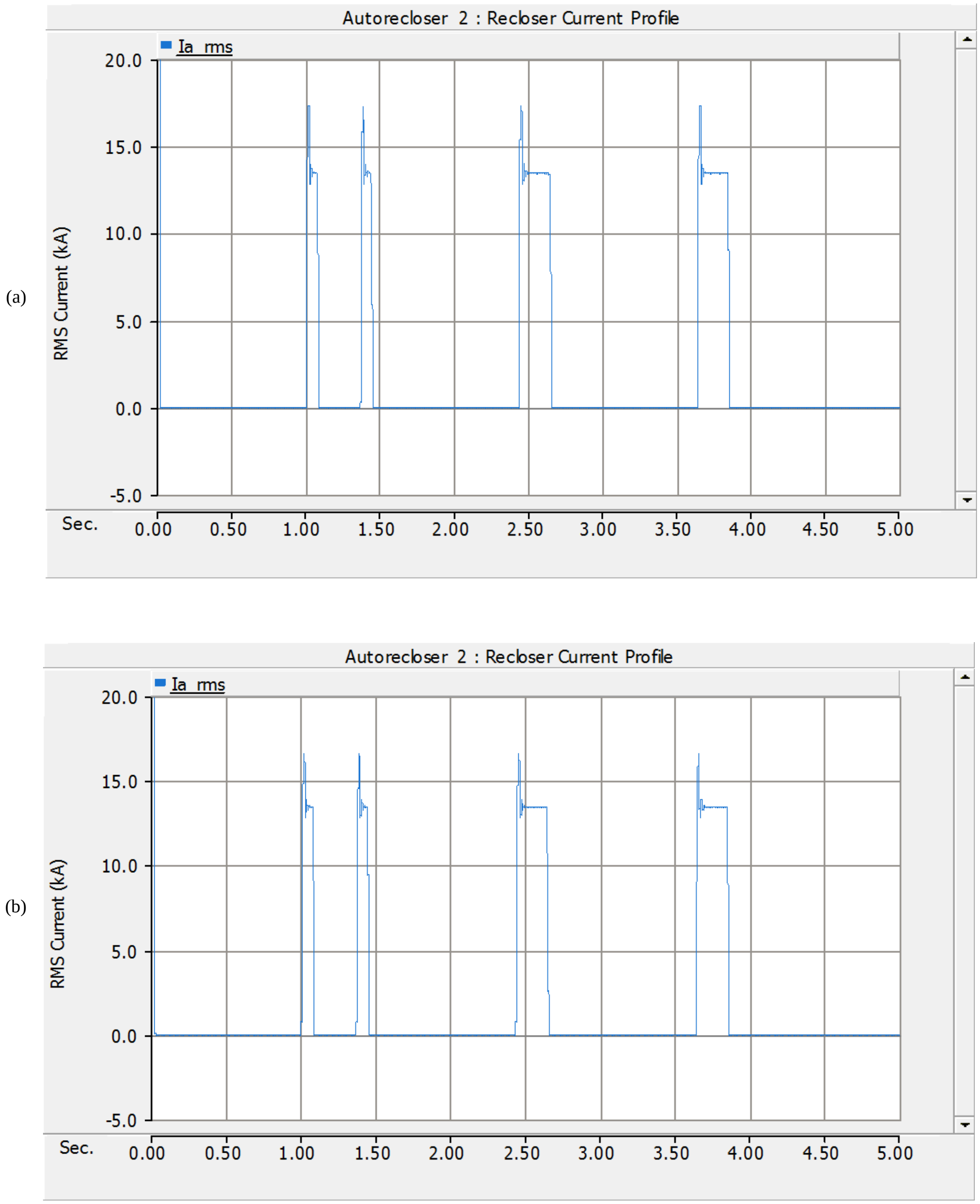


Figure 4.7. Simulated recloser, current profile and sequence of timings for 2-fast, 2-delayed operations: (a) System#1(LFT), (b) System#2 (SST)

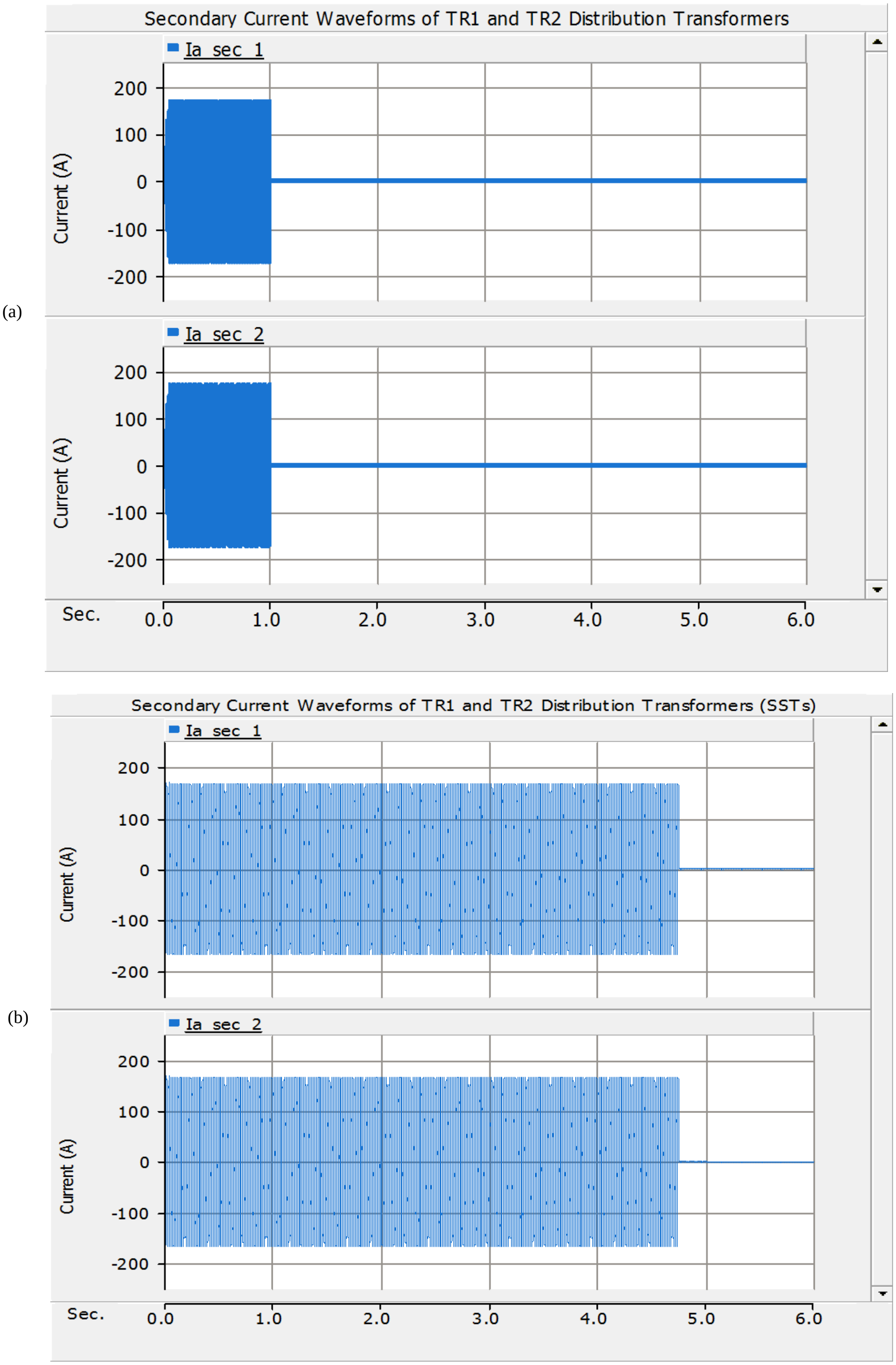


Figure 4.8. Current waveforms at: (a) Loads side for System#1, (b) Loads side for System#2

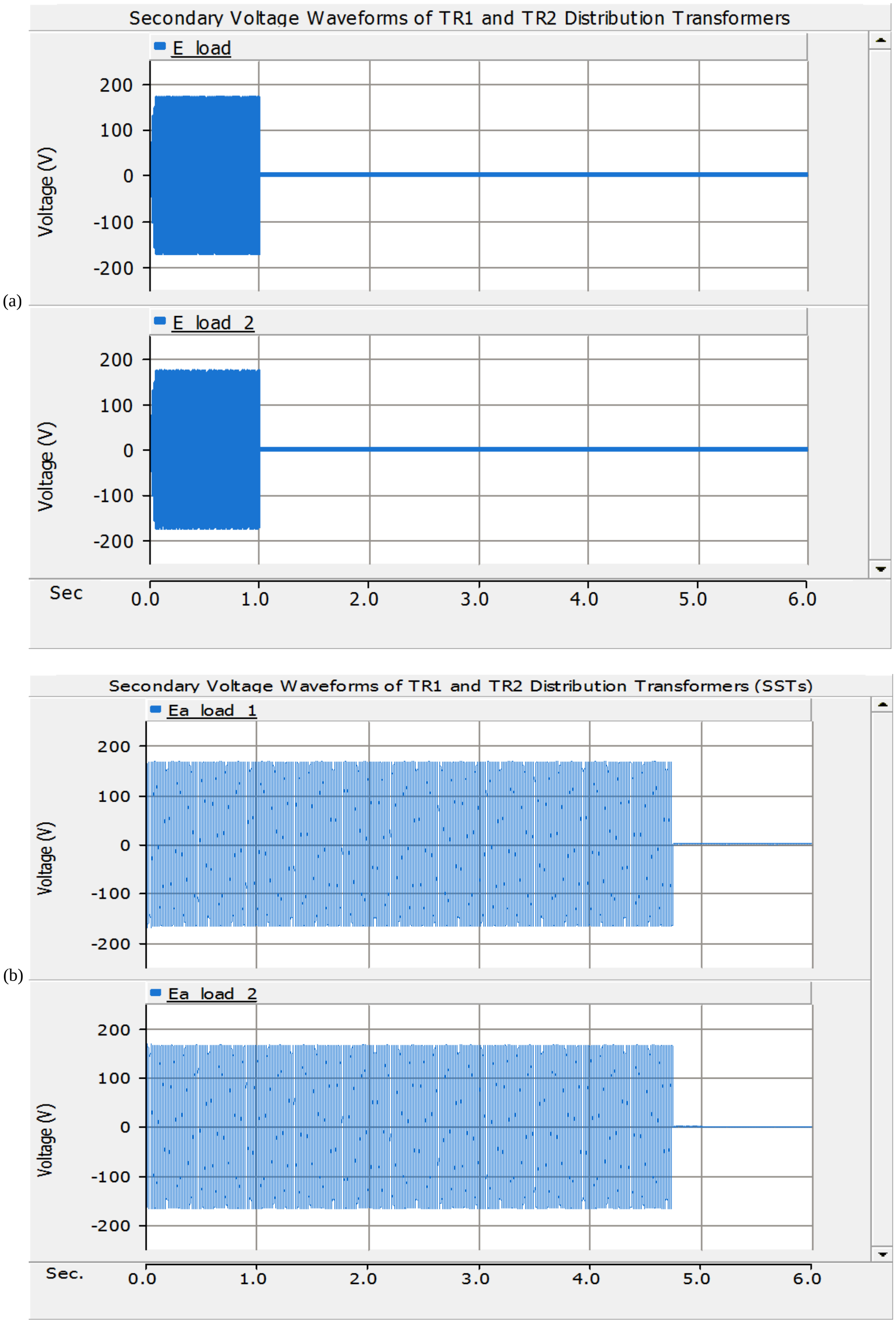


Figure 4.9. Voltage waveforms at: (a) Loads side for System#1, (b) Loads side for System#2

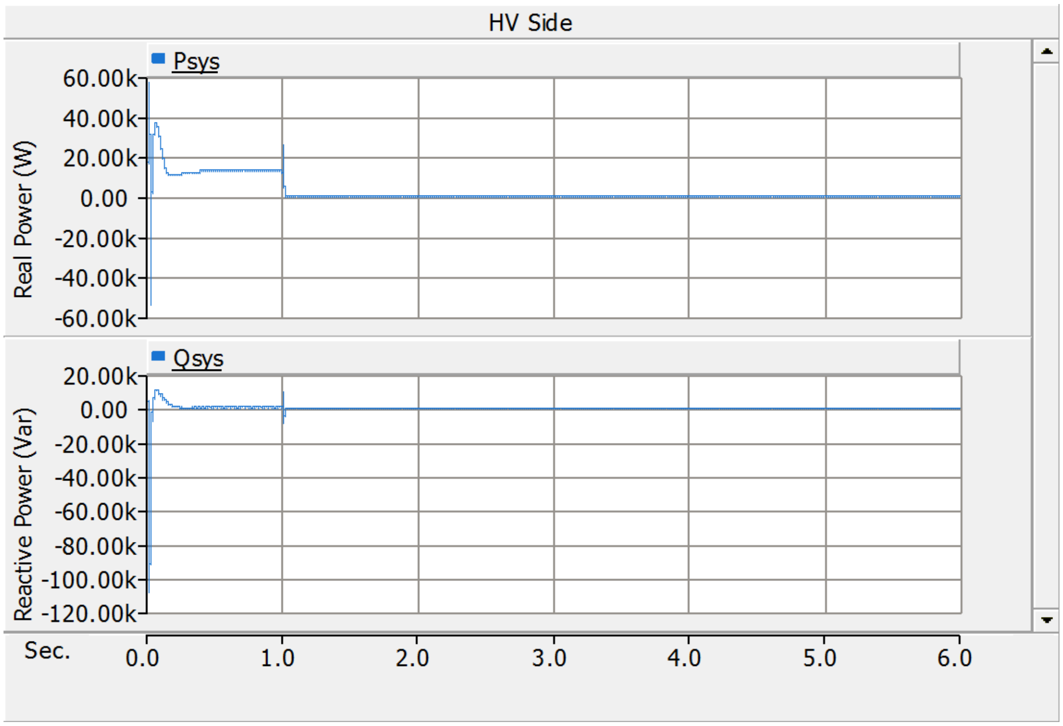


Figure 4.10. SST input active and reactive power during a permanent fault, case 1

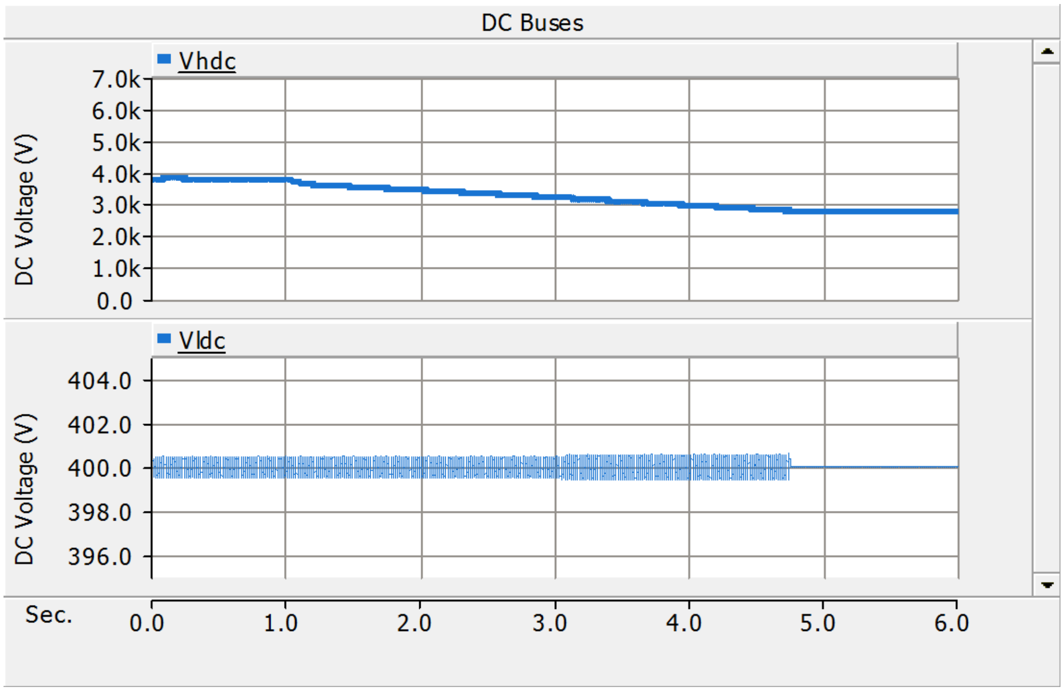


Figure 4.11. DC voltage response during a permanent fault, case 1

4.2.2 Case 2: Temporary SLG Fault on the Main Feeder (One Fast Operation). In this case we describe an initial phase-to-ground fault on a solidly grounded system which may have been caused by touching of a tree branch to phase A and the ground. The fault was self-cleared during the first reclose interval and the system restored.

The fault starts at t = 1s and self-cleared at t = 1.2s. The recloser will act immediately – first fast operation - and will remain open till the end of first reclose interval. Since the fault self-cleared during the first reclose interval, the recloser will not reclose until the first reclose interval is over. Then the supply will be restored in this case after one reclosing shot. Figure 4.13 – Figure 4.18 shows the output of the simulation.

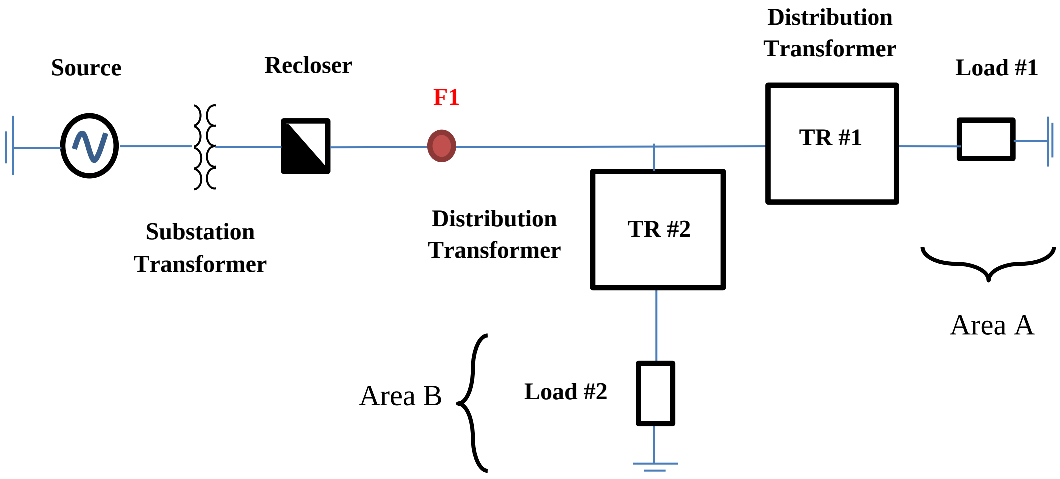


Figure 4.12. The test system for case 2

When a temporary line-to-ground fault occurs in the main feeder, the recloser would measure that fault current and take a decision to operate. Figure 4.13 and Figure 4.14 show the current waveforms due to the operation of the recloser.

Figure 4.15 and 4.16 show the current and voltage waveforms at load side for both System#1 and System#2. We can observe that the customers in Area A&B in System#1 will be out of service until the recloser closes back at about 0.35 second. This time duration of the fault, in this case, is short so the customers will sense a slight blink. On the other hand, customers in the same areas in System#2, who get their supply through SSTs, will continue receiving power. This is, as mentioned in case 1, because the ability of the control circuit of the SST to keep the DC-link voltage as constant as possible.

Figure 4.17and Figure 4.18 demonstrate the SST response under a temporary fault. During the fault, the high voltage DC bus varies around 3.8 kV and the low voltage DC bus is still stable around 400 V. So, the output voltage and current of the SST are not affected by the temporary fault occurred at main feeder.

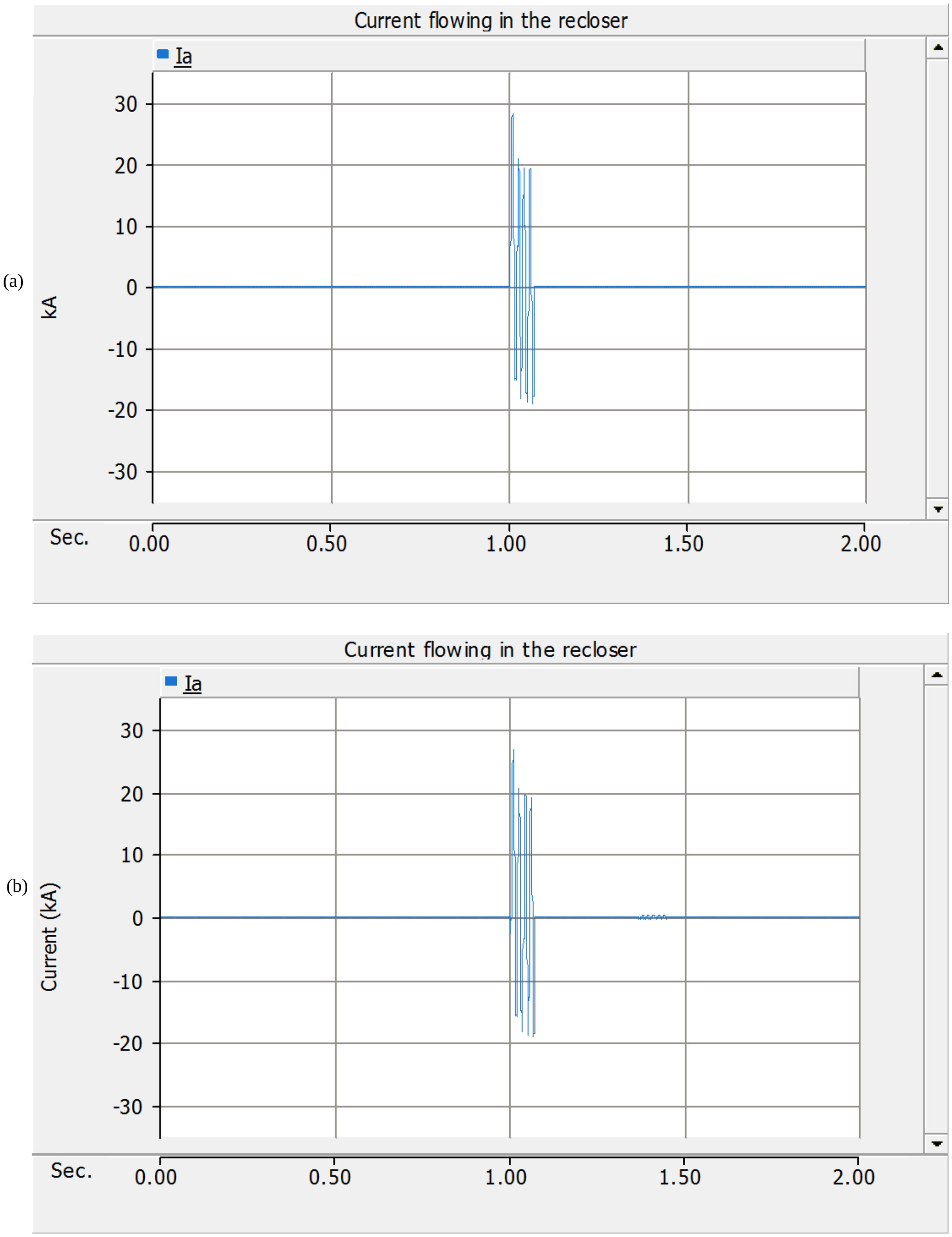


Figure 4.13. Current waveform seen by the recloser: (a) System#1(LFT), (b) System#2 (SST)

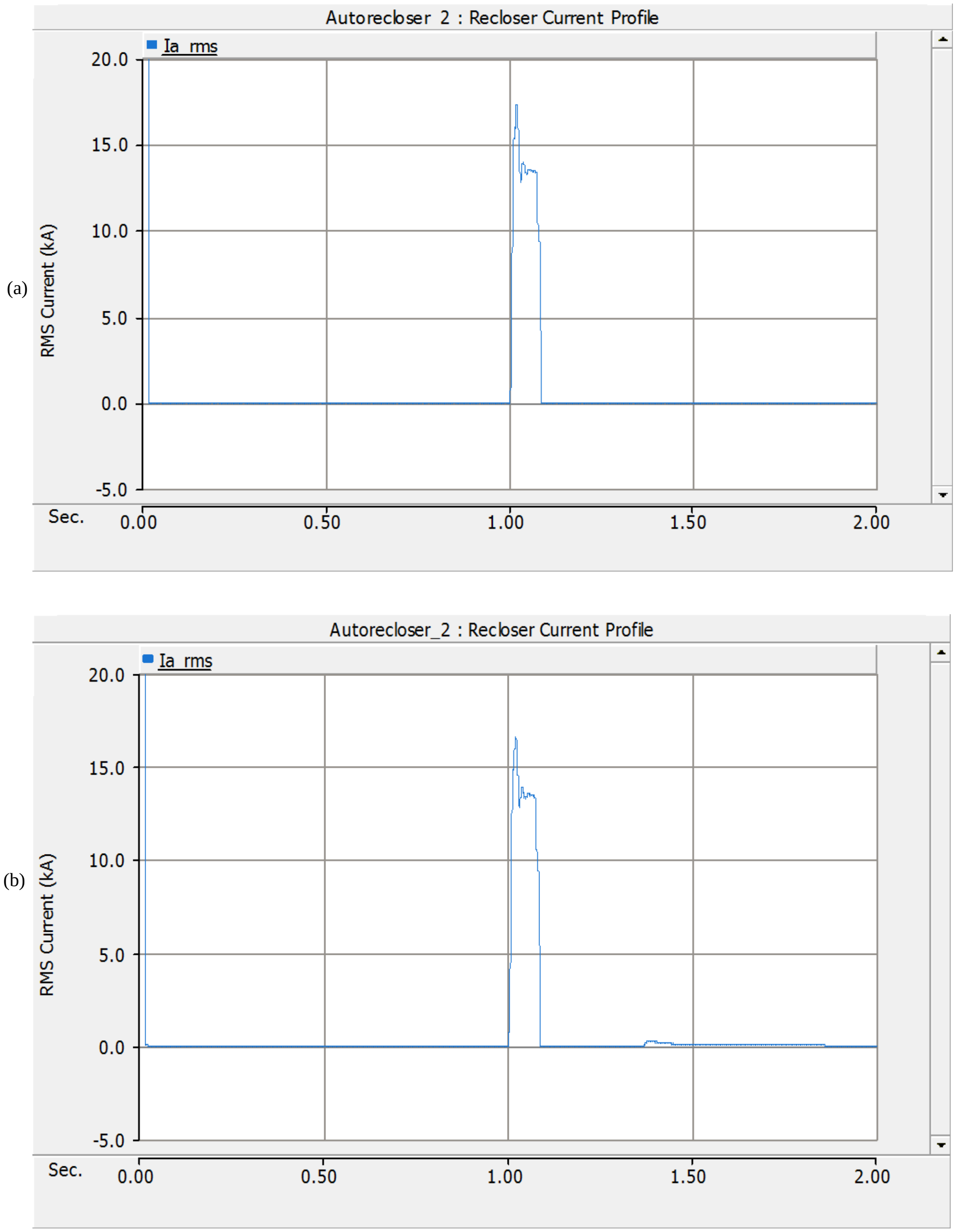


Figure 4.14. Simulated recloser, current profile and sequence of timings for 1-fast operation: (a) System#1(LFT), (b) System#2 (SST)

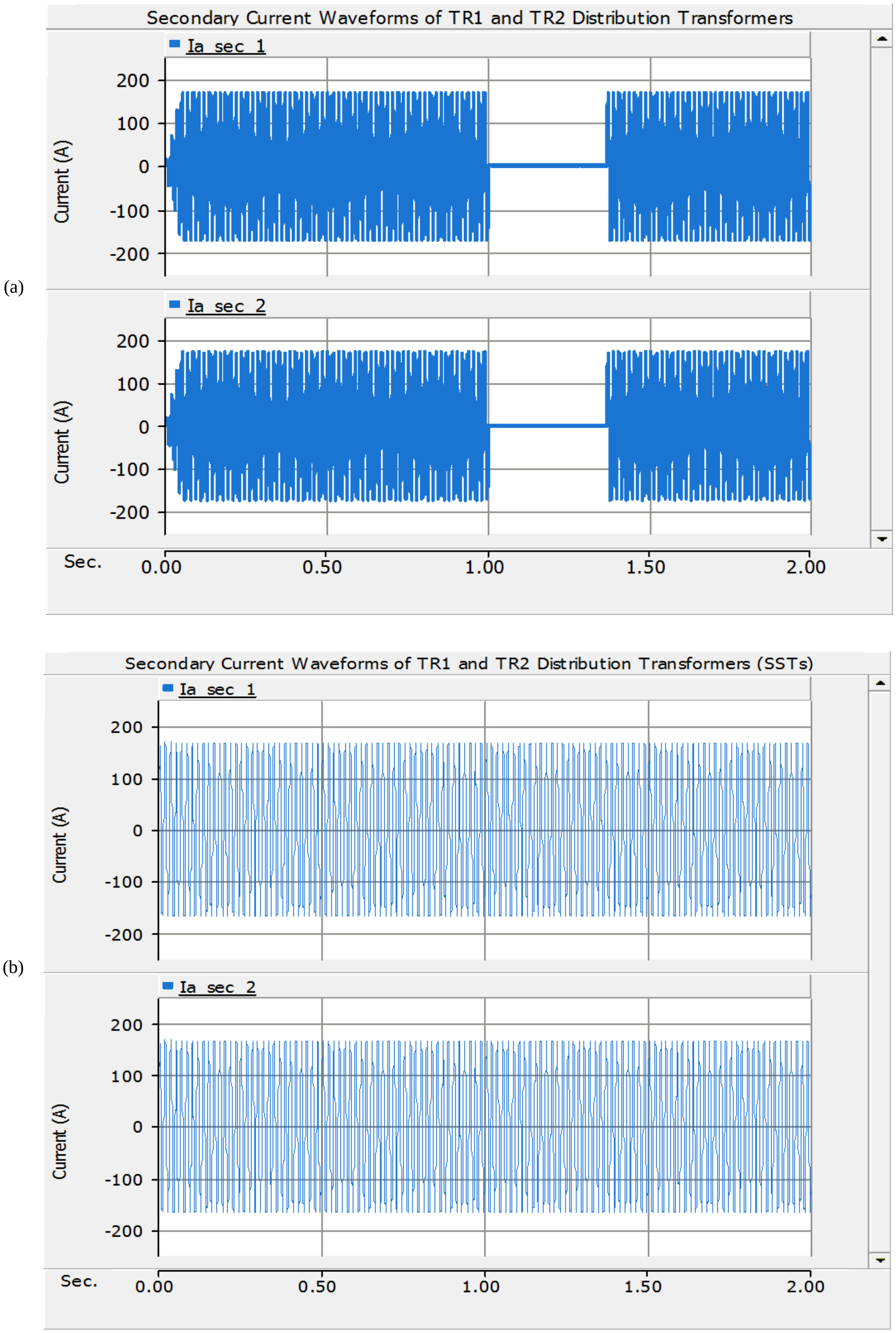


Figure 4.15. Current waveforms at: (a) Loads side for System#1, (b) Loads side for System#2

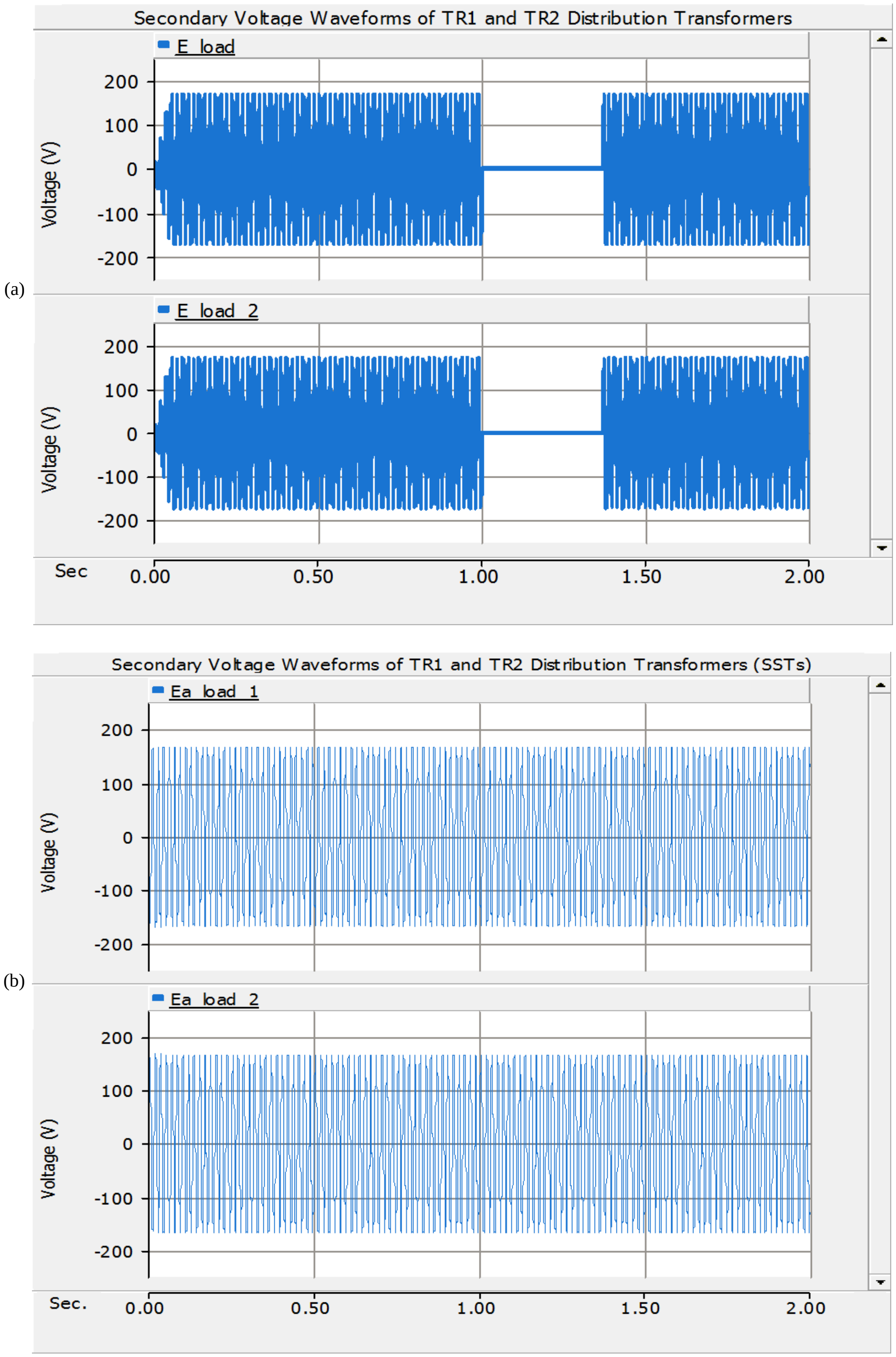


Figure 4.16. Voltage waveforms at: (a) Loads side for System#1, (b) Loads side for System#2

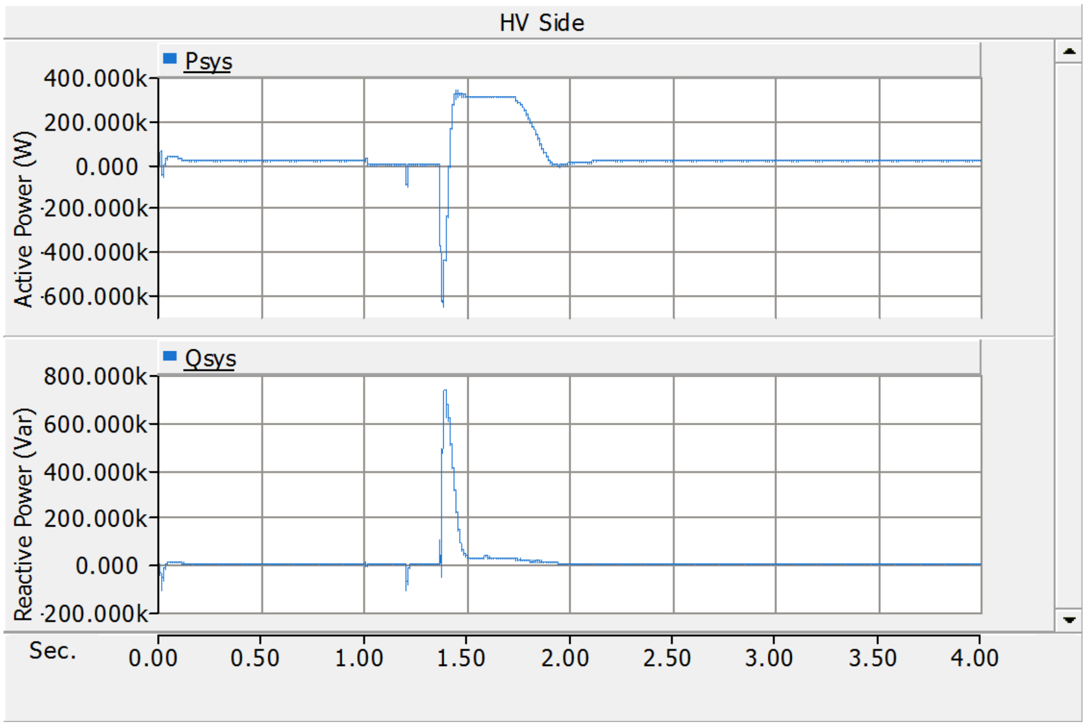


Figure 4.17. SST active and reactive power during a permanent fault, case 2

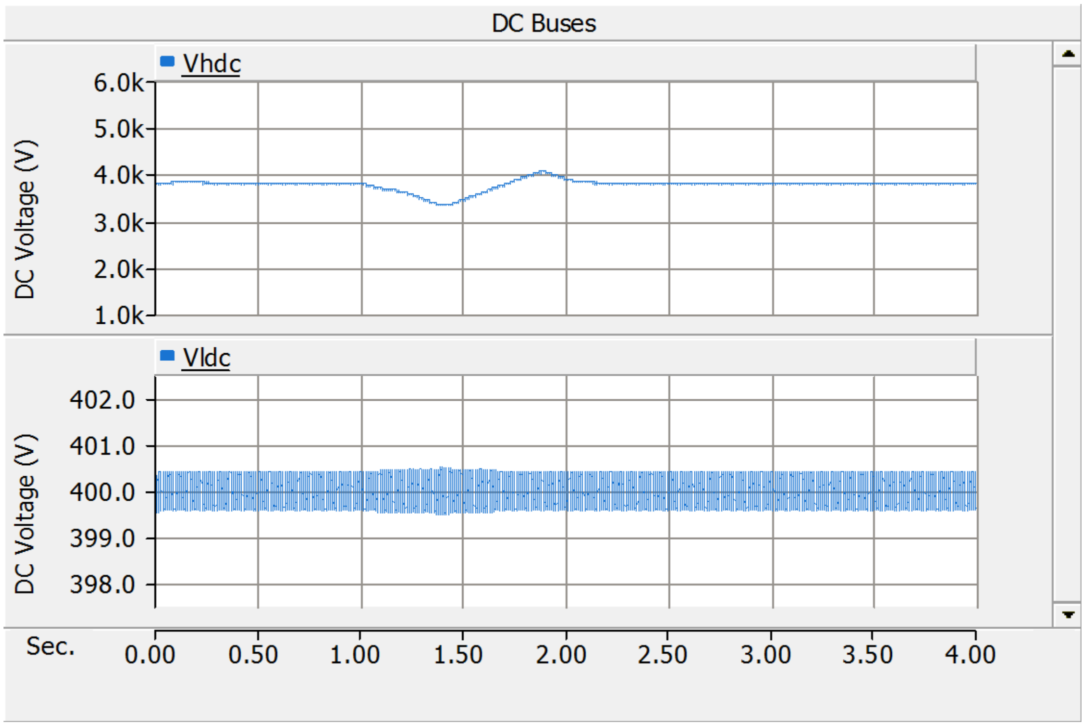


Figure 4.18. DC voltage response during a permanent fault, case 2

4.2.3 Case 3: Permanent SLG Fault at the Load Side of Distribution

Transformer TR#1. In this case, a permanent short circuit (SLG) occurs at t = 1s on the secondary side of TR#1 which is protected by a fuse as shown on Figure 4.19. Since the recloser was designed to help save fuses, it will operate very quickly two times on the fast operation in order to clear the fault before any fuses get melt. Then the fuse will operate and clear the fault by isolating the faulted section. Figure 4.20 – Figure 4.29 shows the outputs of the simulation.

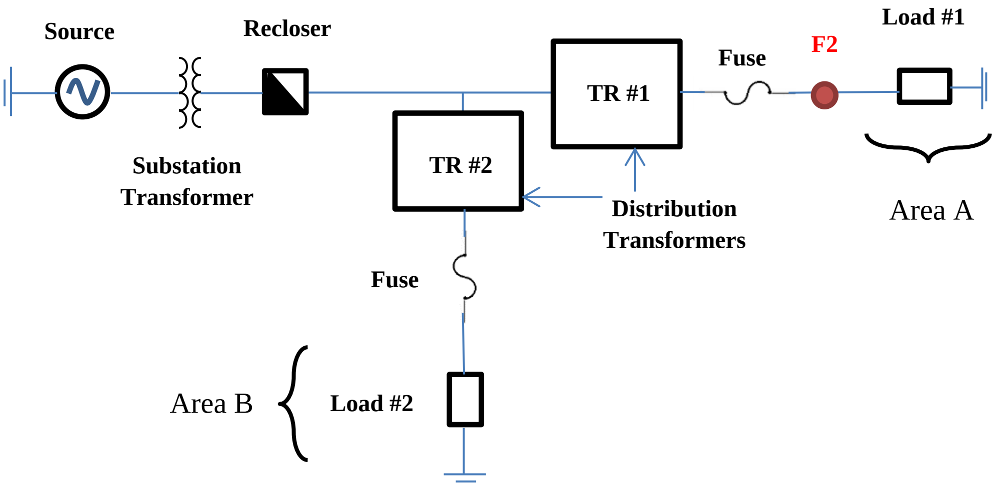


Figure 4.19. The test system for case 3

Figure 4.20 and Figure 4.21 show the current and voltage waveforms at load side for System#1. Customers in Area A in System#1 will experience an outage starting at the fault time (t=1s.), while customers in Area B will experience a momentary interruptions as slight blink due to the operation of the recloser. Figure 4.21 shows the current flowing in the recloser.

At the moment of SLG fault in System#2 (SST), current flowing through the SST#1 into ground is large as shown in Figure 4.23. But the current in the primary side does not increase to a high value as in System#1. Figure 4.24 shows the primary current flowing in the recloser. So, we can observe that the fault on the secondary of the SST does not result in an increase in the primary current which means the recloser will not see a fault current in this case. As a result, no need to set a recloser in fuse saving scheme if the distribution transformer used is SST. So, if a permanent fault occurs at the secondary of the SST, the fuse will operate and isolate the fault as shown in Figure 4.23. Customers in Area B will not experience any momentary interruption as shown in Figure 4.25 because the recloser did not operate.

Figure 4.26 and Figure 4.27 demonstrate the SST, in Area A, response under a temporary fault on the secondary side. The SST response for Area B, unaffected Area, is shown in Figure 4.28 and Figure 4.29.

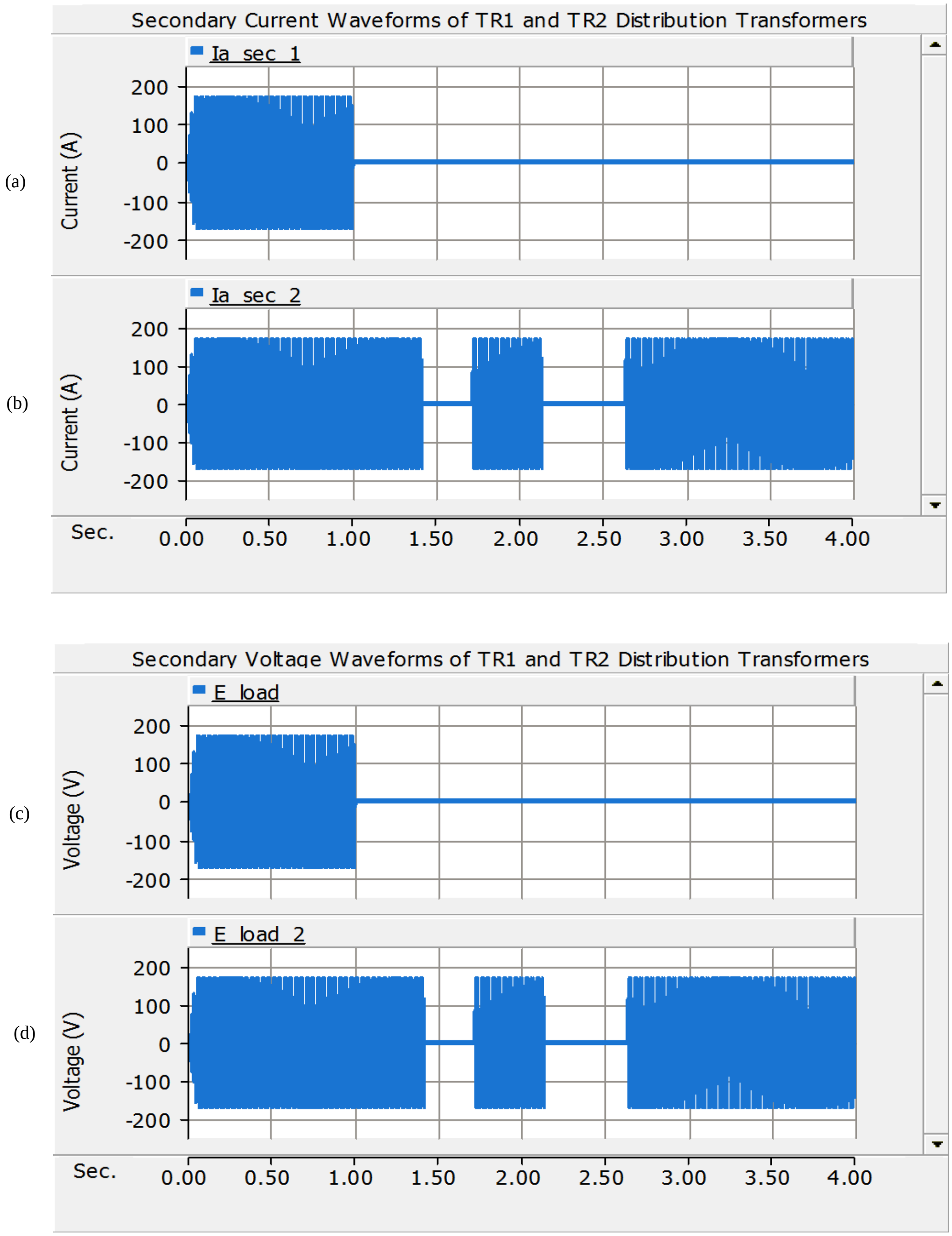


Figure 4.20. System#1 (LFT) current and voltage waveforms at: (a) Load#1 current, (b) Load#2 current, (c) Load#1 voltage, (d) Load#2 voltage

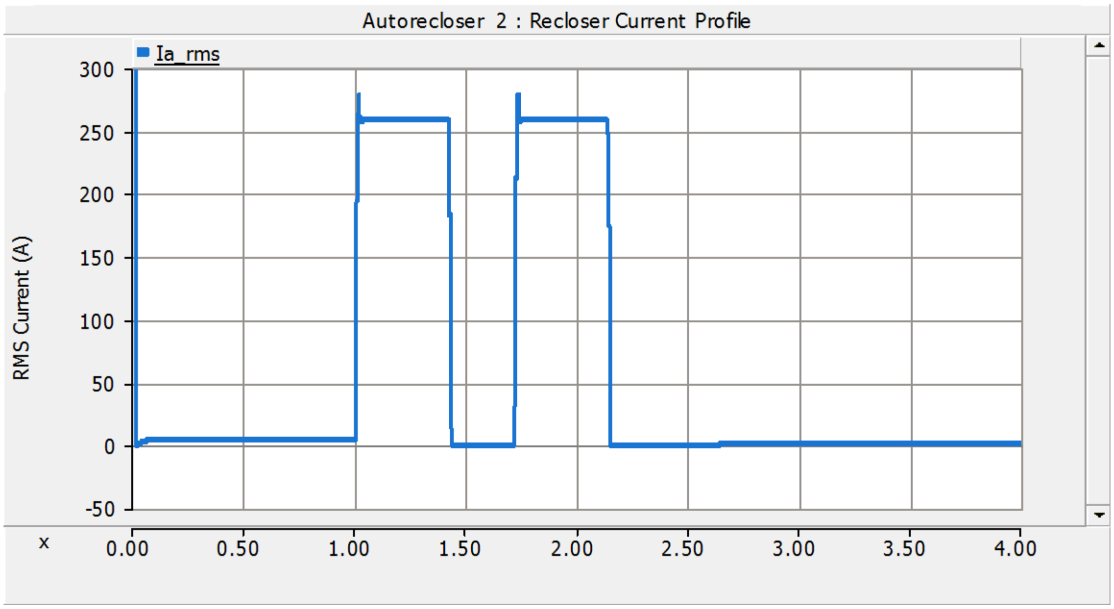


Figure 4.21. Simulated recloser, current profile and sequence of timings for System#1(LFT), case 3

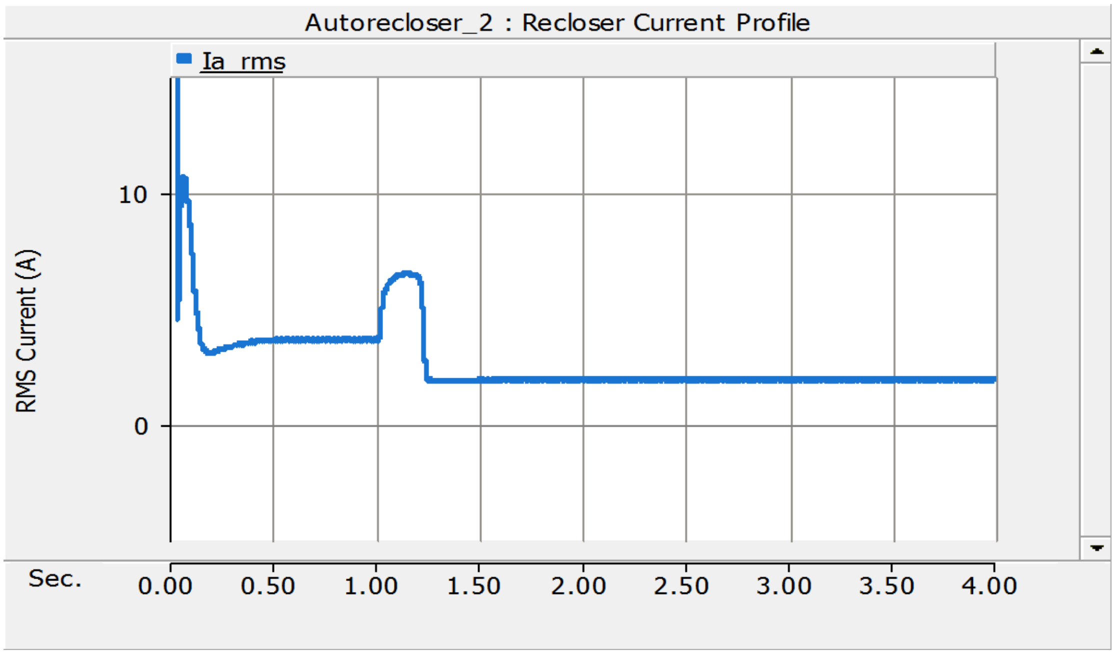


Figure 4.22. Simulated recloser, current profile and sequence of timings for System#2(SST), case 3

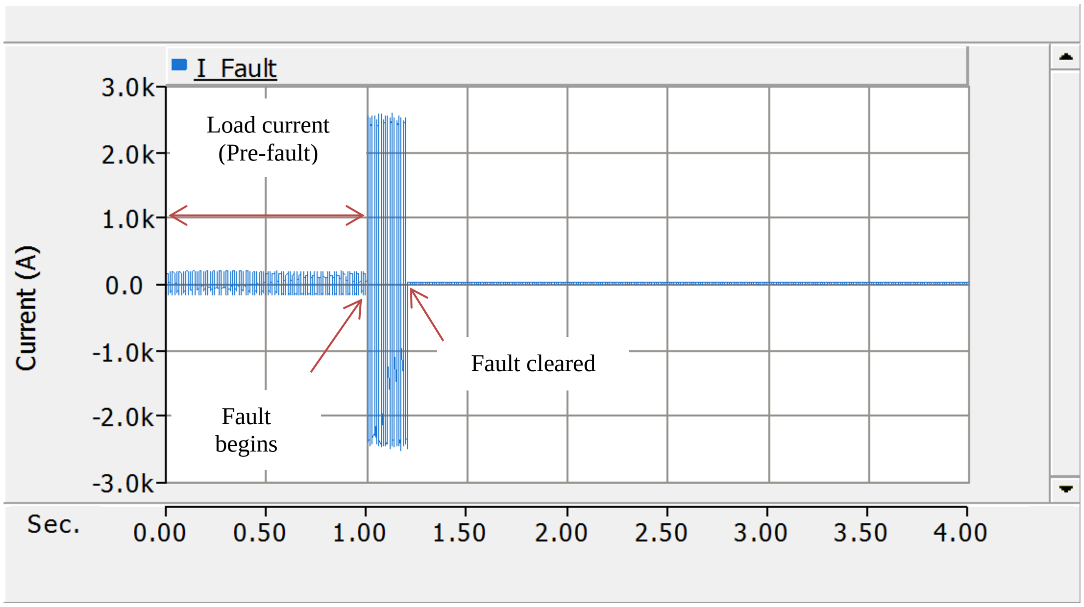


Figure 4.23. Current waveform between the secondary of SST#1 and fault location

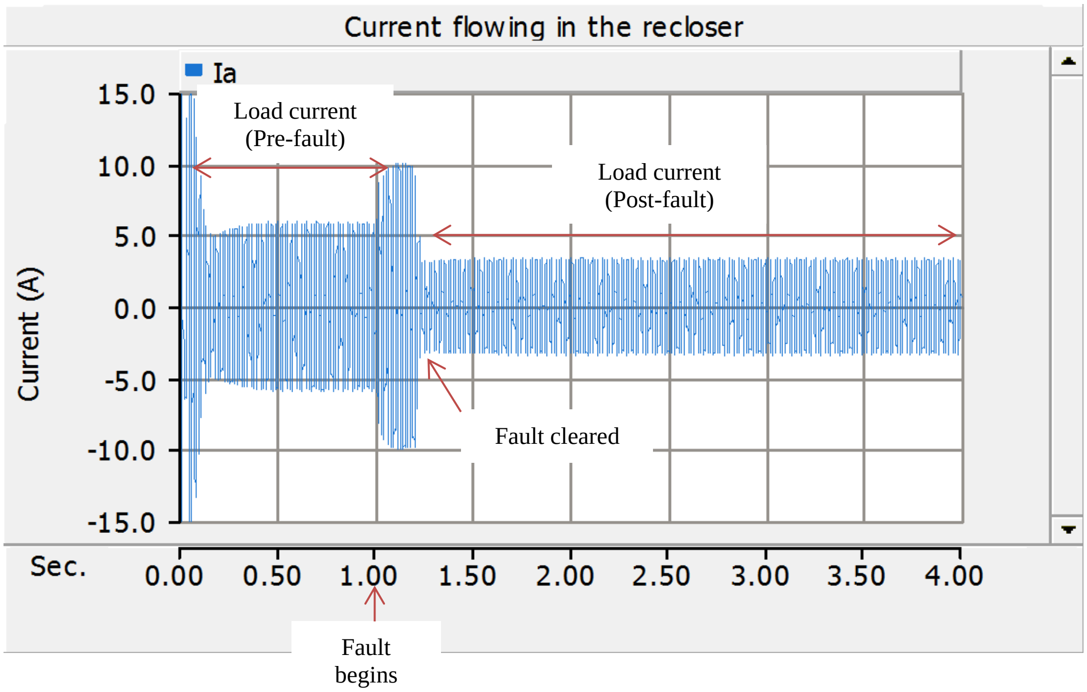


Figure 4.24. Current flowing in the recloser of System#2, case 3

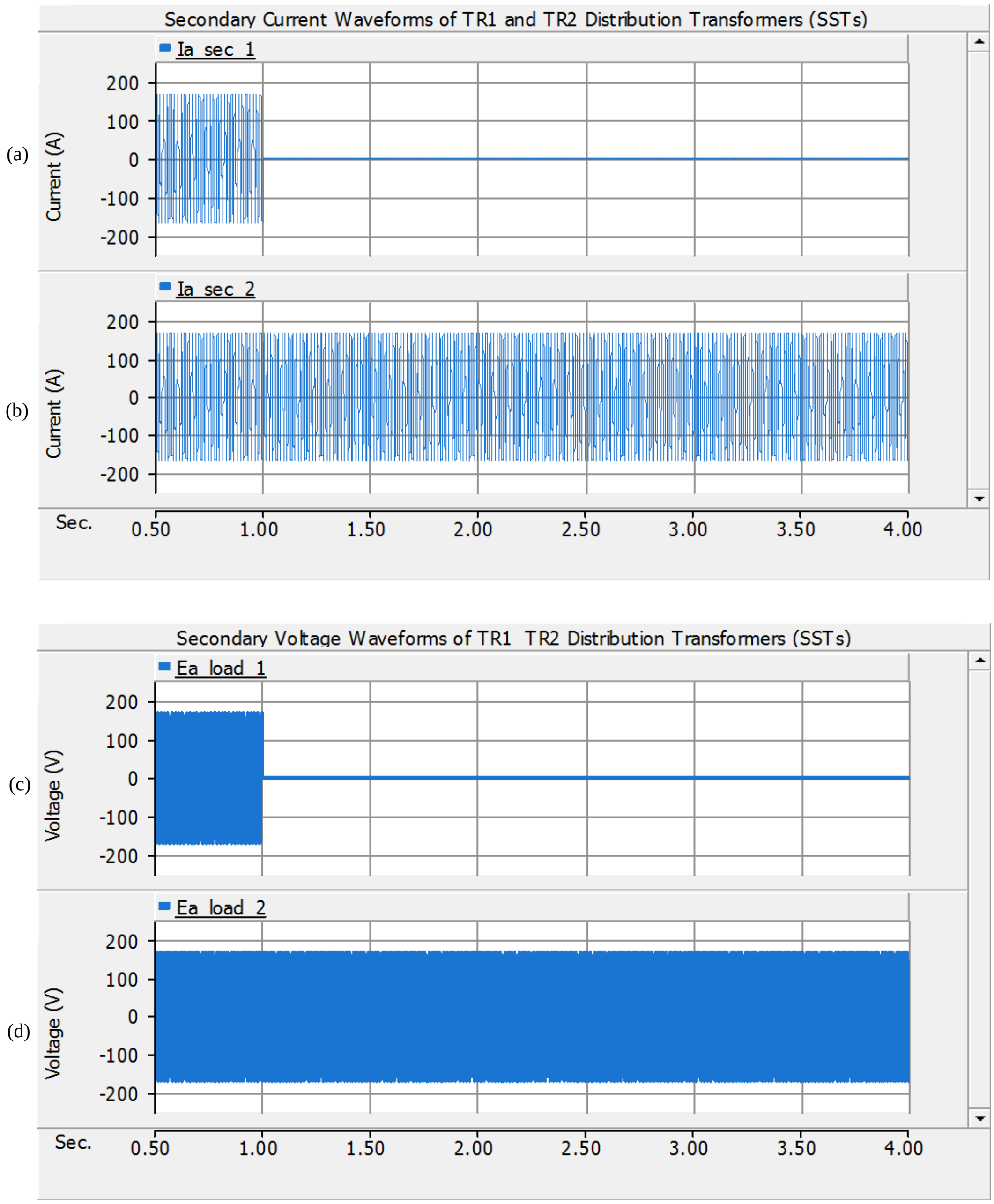


Figure 4.25. System#2 (SST) current and voltage waveforms at: (a) Load#1 current, (b) Load#2 current, (c) Load#1 voltage, (d) Load#2 voltage

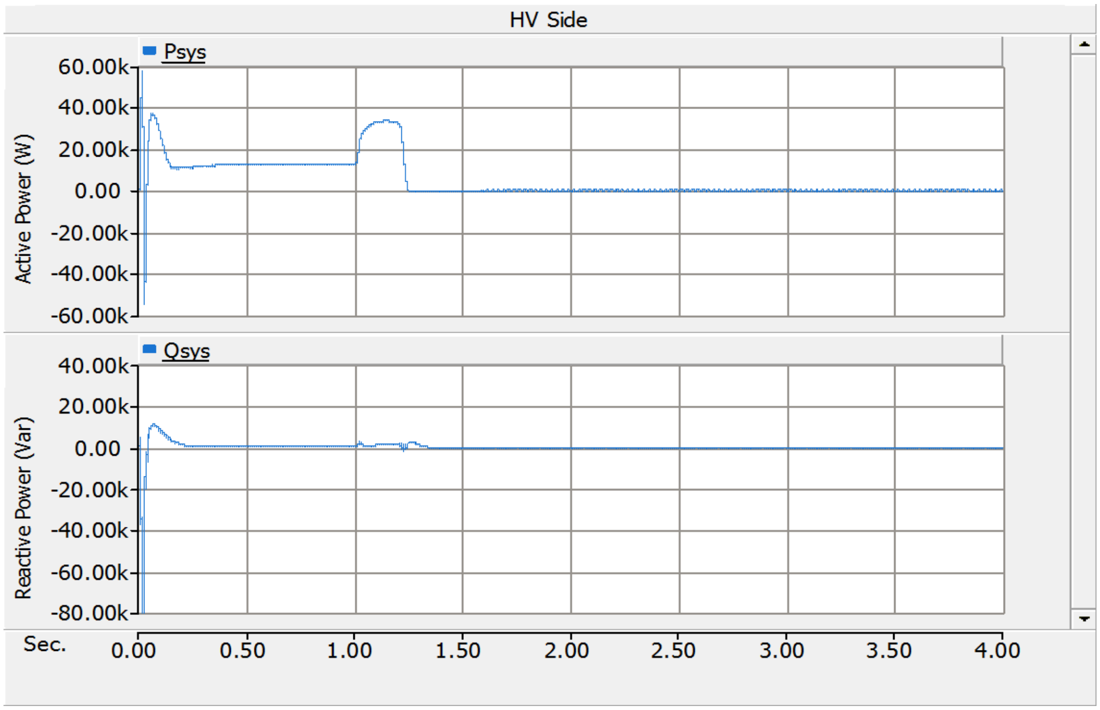


Figure 4.26. SST#1 active and reactive power during a permanent fault, case 3

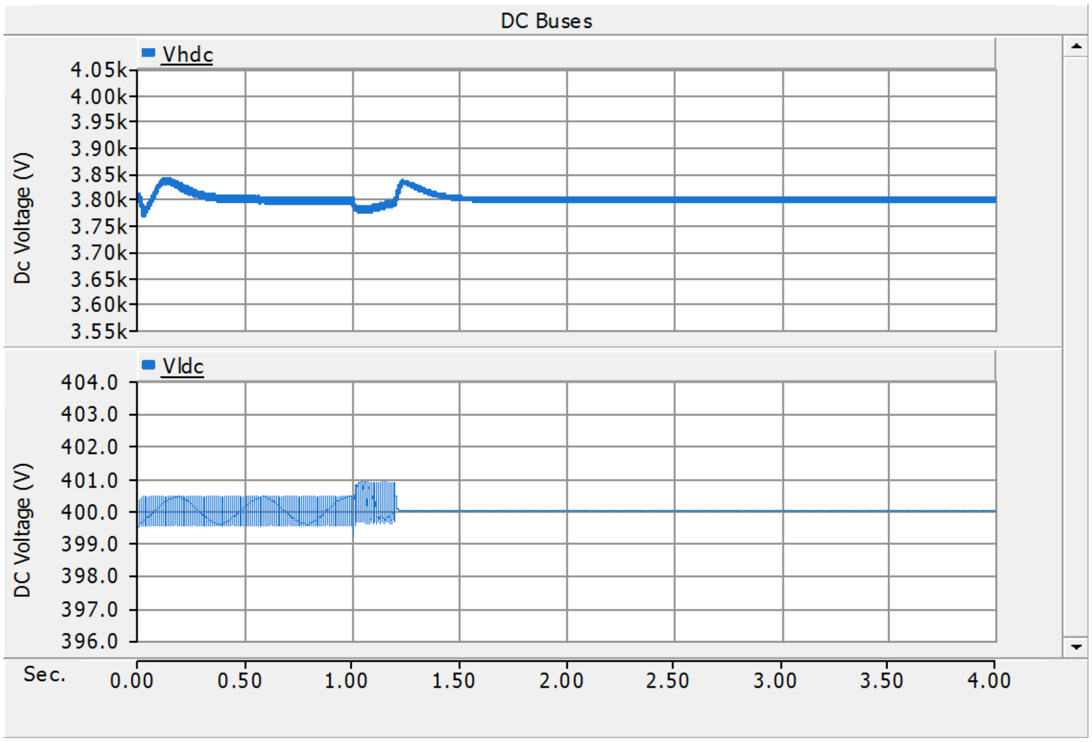


Figure 4.27. DC voltage response during a permanent fault, case 3

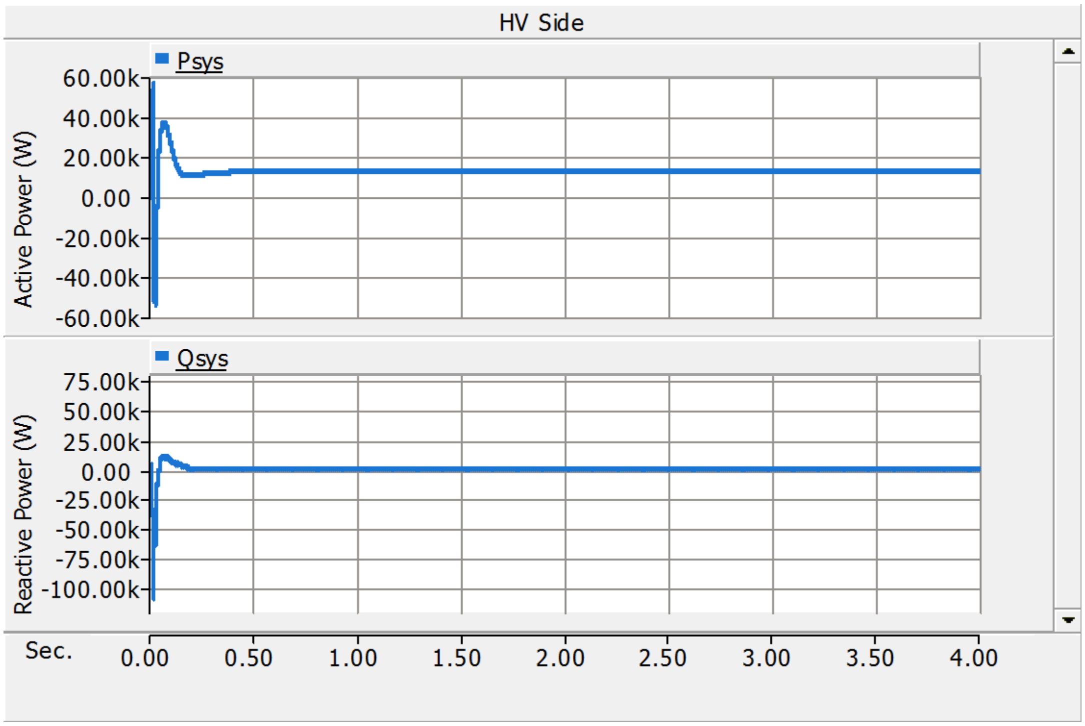


Figure 4.28. SST#2 active and reactive power during a permanent fault, case 3

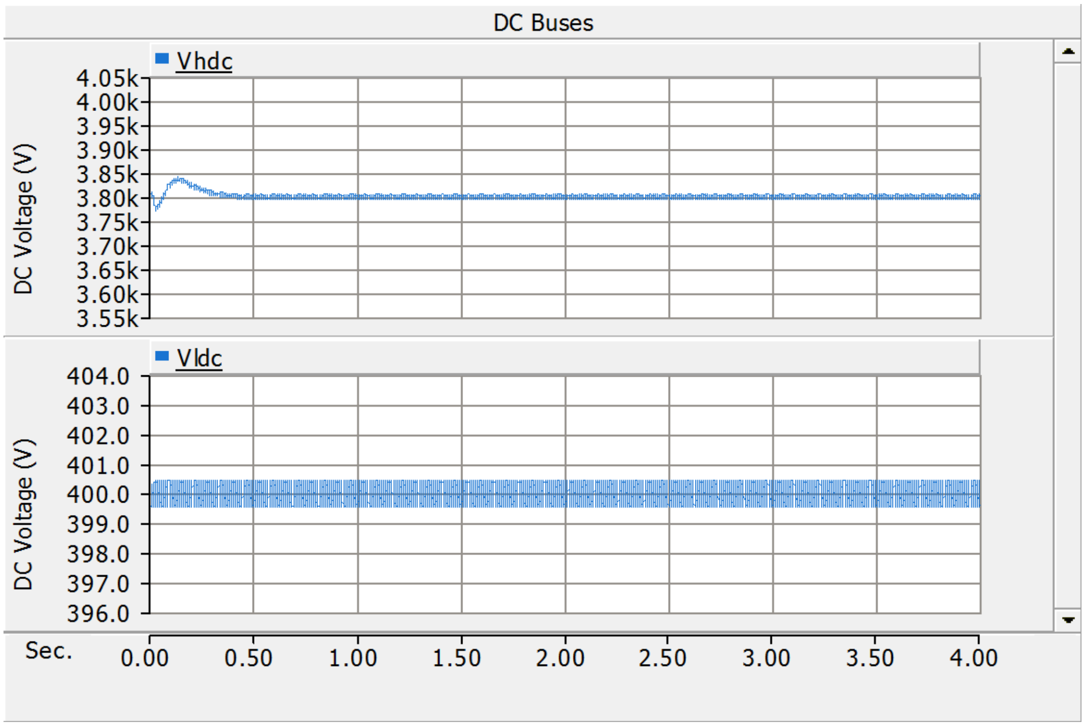


Figure 4.29. DC voltage response for SST#2 during a permanent fault, case 3

4.2.4 Case 4: Permanent SLG Fault at the Load Side of Distribution Transformer TR#2.

A permanent single line-to-ground (SLG) fault is applied on Load 2a connected to the secondary of distribution transformer TR#2 (SST) as shown in Figure 4.30. In this case the fuse will operate and isolate the fault. The main purpose of this case is studying the behavior of the SST if two loads connected to its secondary side and a SLG fault occurred on one of these loads. The first load, Load 2a, is connected between LVn and GND and the second load, Load 2b, is connected between LPn and GND as shown in Figure 4.30. Each load is connected to 120 V port. The fault starts at t = 1s on Load 2a side. Figure 4.31 – Figure 4.34 shows the outputs of the simulation.

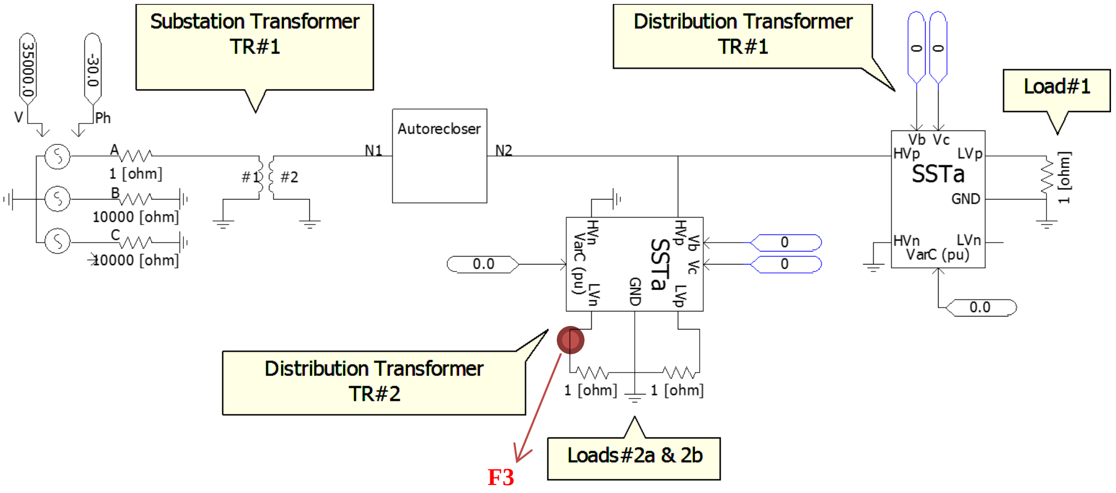


Figure 4.30. Test system for case 4

In this simulation, a single line-to-ground fault starts at 1s on the output port LNv, and persists as a permanent fault. Whereas the output port LVp remains healthy. Once the fault occurs, the fuse operates to isolate it immediately. Customers connected to that port will experience an outage, while customers on the other port will not experience any interruptions. Figure 4.31 shows the primary current flowing in the recloser before, during and after the fault. Figure 4.32 shows the current and voltage waveforms at loads 2a and 2b. Figure 4.33 and Figure 4.34 demonstrate the SST#2 response under a permanent fault on the secondary side.

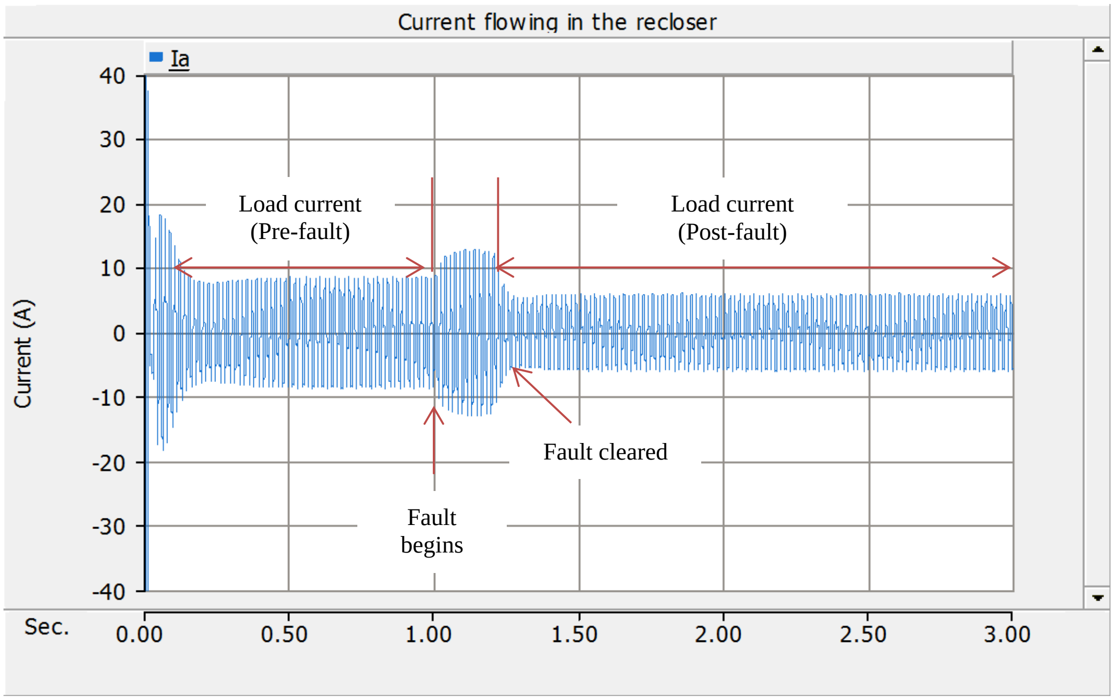


Figure 4.31. Current flowing in the recloser, case 4

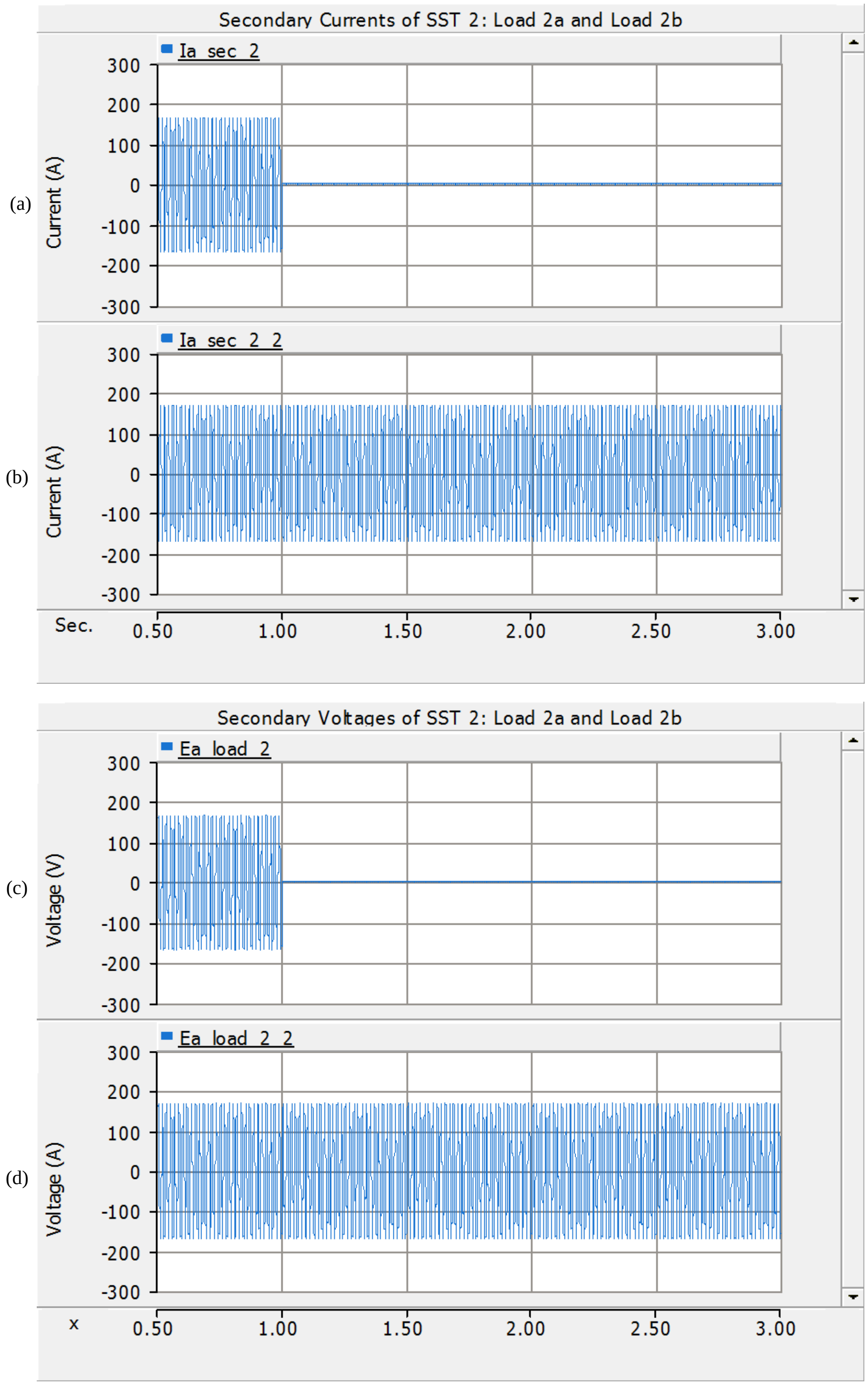


Figure 4.32. Current and voltage waveforms at: (a) Load 2a current, (b) Load 2b current, (c) Load 2a voltage, (d) Load 2b voltage

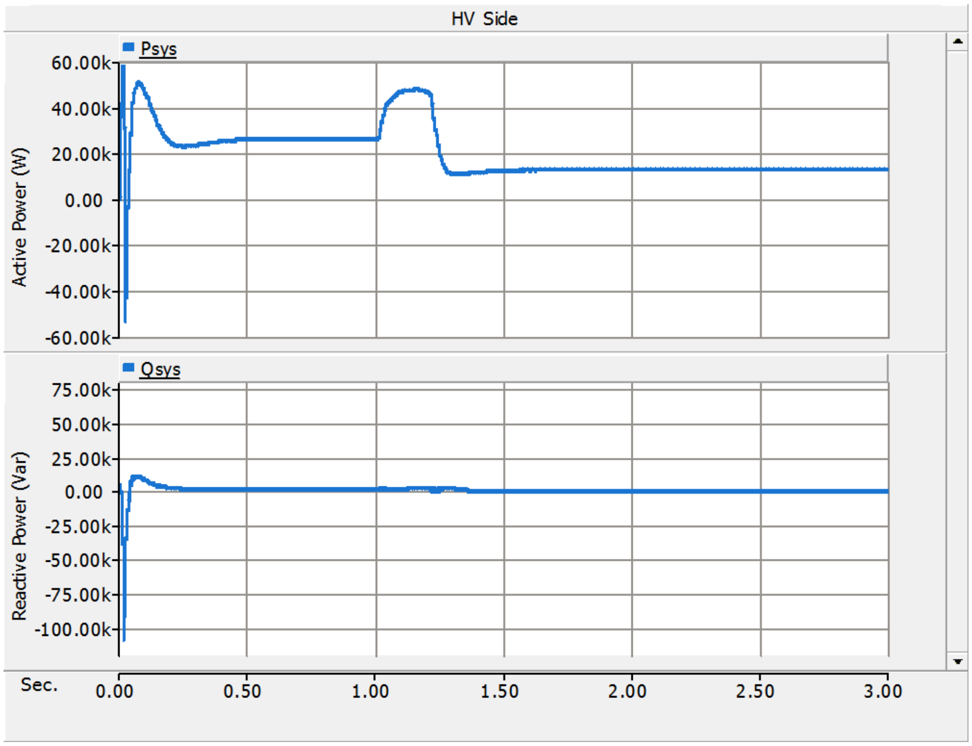


Figure 4.33. SST#2 active and reactive power during a permanent fault, case 4

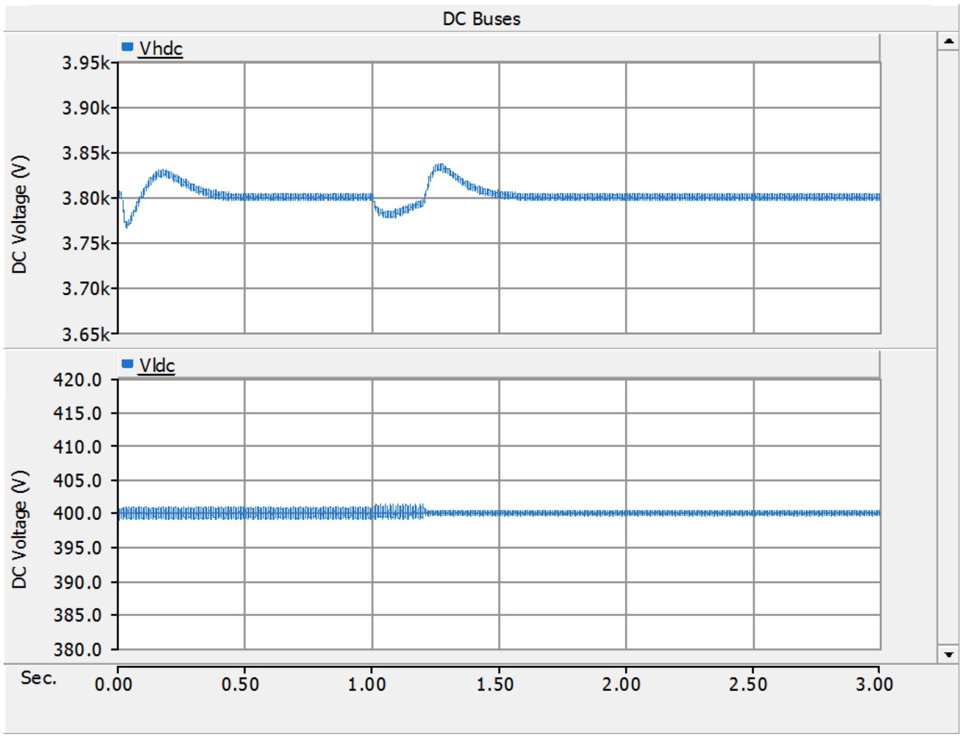


Figure 4.34. DC voltage response during a permanent fault, case 4

4.3 SUMMARY

This section presents the behavior of the SST under the operation of protective devices such as autorecloser and fuse. An autorecloser is the protective device used to protect the main feeder (the primary side of the SSTs) and the fuse was used to protect the secondary side of the transformers. The following was observed from the results of the several cases:

- The SST has the ability to compensate for the voltage drop on the high side due to the energy stored in the DC bus capacitance. Therefore the disturbance does not propagate through to the low side of the SST.
- A different behavior is observed when a single line-to-ground fault occurs at the high side of the SST. In case of permanent fault at high side, the customers will not experience any interruptions due to the operation of the recloser and they still get power for more cycles compared to the customers connected to the traditional line frequency transformer (LFT).
- For SLG fault at the secondary of the SST, the coordination between the recloser and the fuse is not necessary. That is because the SST has the capability to not transfer the disturbances to the other side.
- The simulation results show that, in general, the SST is compliant with the traditional system such as a recloser and fuse.
- If two different loads are connected to each port of the SST secondary and a fault occurs at one of these loads, the fuse will operate to clear and isolate the fault without affecting the healthy port which does not experience any disturbance.

5. CONCLUSIONS AND FUTURE WORK

The research objective was to study the behavior of SST under fault conditions in a distribution system. In order to achieve this goal, a recloser model was designed in PSCAD®/EMTDC™ software.

An overview of distribution system protection was provided in Section 2. The recloser model was developed and validated under different conditions in Section 3 by using PSCAD®/EMTDC™. The same recloser model was used in Section 4 once along with the traditional line frequency transformer (LFT) and once along with the SST. A comparison was presented between these two types of transformers and their behaviors during operation of protective devices.

Investigation of the SST behavior under different conditions shows the following:

- The ability to compensate for the voltage drop on both sides of the SST due to the energy stored in the DC bus capacitance. Therefore the disturbance does not propagate between the two sides.
- The operation of the recloser due to a permanent single line-to-ground fault on the high voltage side of the SST has no effect on customers on the low voltage side. Moreover, customers still get power for few cycles compared to the customers connected to the traditional line frequency transformer (LFT).
- For SLG fault at the secondary of the SST, the coordination between the recloser and the fuse is not necessary. That is because the SST has the capability to not transfer the disturbances to the other side.

- The simulation results show that, in general, the SST is compliant with the traditional protection devices such as a recloser and fuse.
- If two different loads connected to each port of the SST secondary and a fault occurs at one of these loads, the fuse will operate to clear and isolate the fault without affecting the healthy port which does not experience any disturbance.

The future work of this research includes:

- Large real distribution system. The SST needs to work in proper way and as expected with the traditional power grid.
- Three phase distribution system. In this research, we concentrated on a small single phase system with resistive loads in order to limit the number of variables.
- Impact of various load types on SST operation.
- Impacts of various protective devices as well as protection schemes on SST operation.

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VITA

Fahd Amin Hariri was born on November 29, 1981 in Al-Madinah, Saudi Arabia. He received his Bachelor of Engineering degree in Electrical Engineering from the King Abdul Aziz University, Jeddah, Saudi Arabia in December 2004.

From 2005 to 2009, he has been a transmission engineer at Saudi Electricity Company, Jeddah, Saudi Arabia. Since 2009, he has been teaching assistant at Electrical Engineering Department, King Abdul Aziz University.

Since 2013, he has been working toward the M.Sc. degree in Electrical Engineering at Missouri University of Science and Technology under the direction of Prof. Mariesa Crow. He obtained his Master’s degree in August 2015.