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Automated Algorithms to Identify Operations of Overcurrent Protective Devices: A Proof of Concept

Technical Report

Automated Algorithms to Identify Operations of Overcurrent Protective Devices: A Proof of Concept

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PRODUCT DESCRIPTION

Overcurrent protection in distribution systems involves the coordination between different levels of protective devices. Time settings of these devices are determined in protection coordination studies and subsequently programmed into overcurrent relays. Unfortunately, there are instances where poor or mis-coordination occurs. Under such circumstances, power quality and reliability will be adversely impacted. This report presents a proof of concept algorithm to identify the operation of overcurrent protective devices, especially fuses and line reclosers. The algorithm represents an initial step in developing a fully automatic analysis system to evaluate distribution system overcurrent protection coordination.

Results & Findings

The project successfully developed an algorithm for identifying fuse and recloser operation. The accuracy of the algorithm was demonstrated by applying it to analyze data generated using time-domain simulation models as well as data collected from actual distribution systems.

Challenges & Objectives

The objective of the algorithm is to identify what types of protective devices may have operated during faults detected by power quality monitors or other waveform recording devices such as digital relays. This information helps the user when interpreting fault waveforms. The challenges of the project included how to model the operation of protective devices, how to identify the fault component of the current waveform, and finding good data to verify the performance of the algorithm.

Applications, Values & Use

The algorithm can be implemented in a stand-alone software program or as an add-on to identify fuse or line recloser operations. It can be used to help locate faults and evaluate recloser-fuse coordination.

EPRI Perspective

The algorithm developed here can help power quality engineers interpret waveforms, and it can provide information that can help protection engineers diagnose coordination issues. This project also sets the stage for other projects: portions of the algorithm for identifying fault characteristics can be useful for fault location and more advanced fault signature evaluation.

Approach

The algorithm works by estimating the fault current magnitude seen by the protective device and the duration during which the fault current flows in the device. The algorithm then determines which protective device time-current characteristic curves match these two parameters the closest. The closest matches are identified as the protective devices that operated to interrupt the fault current.

Keywords

Distribution system
Overcurrent protective devices
Power quality
Fuses
Reclosers
Time-current characteristic curves

ABSTRACT

Overcurrent protection in distribution systems involves the coordination between different levels of protective devices. Time settings of these devices are determined in protection coordination studies and subsequently programmed into overcurrent relays. Unfortunately, there are instances where poor or mis-coordination occurs. Certainly, under such circumstances, power quality and reliability will be adversely impacted.

This report presents a proof of concept algorithm to identify the operation of overcurrent protective devices, especially fuses and line reclosers. The algorithm represents an initial step in developing a fully automatic analysis system to evaluate the coordination of distribution system overcurrent protective devices. The identifier algorithm, at minimum, requires three-phase voltage and current waveforms captured upstream from overcurrent devices being monitored. In addition, the algorithm needs to know the utility fault clearing scheme, i.e., whether it is based on the fuse saving or fuse blowing scheme. Data on types of overcurrent protective devices used in the distribution feeders and their corresponding TCC curves are not required although they are desirable. When they are not provided, the algorithm assumes that the distribution feeders use all types of K and T fuses.

The algorithm works by estimating the fault current magnitude seen by the protective device and the duration during which the fault current flows in the device. The algorithm then determines which protective device time-current characteristic curves match these two parameters the closest. Ones that do are considered as the protective devices that operate to interrupt the fault current. This is essentially how the algorithm identifies fuse operations. In this initial work, we consider all types of K and T link fuses.

Identifying recloser operations is more complex since there are several shots in the fault clearing sequence. In particular, this report assumes a four-shot sequence, i.e., two fast and two delayed operations. The entire clearing sequence may take one or more seconds. Since most power quality monitors do not record disturbance waveform for duration of one second, the sequence is partitioned into several disturbance events. The algorithm assumes that all events are independent and only the first two fast operations are analyzed.

The efficacy of the algorithm is demonstrated using data generated by the time-domain simulation and real-world distribution data. Accuracy of the results is promising and satisfactory. It indicates correct approaches and analysis techniques have been properly implemented in developing the algorithm.

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INTRODUCTION

1.1 Background and Motivation

A radial distribution system is designed for unidirectional electric power flow. In such a system, electric power is delivered from a single source at the substation to a multitude of loads through distribution feeders. Because of this configuration, a radial distribution system requires only one fault interrupter to clear a fault. For permanent faults, a fault interrupter operates to sectionalize the feeder. This action isolates the fault and restores electrical power to the rest of the loads served from the sound sections. Orchestrating the fault clearing process is referred to as the coordination of overcurrent protection devices.

Overcurrent protection devices include circuit breakers, reclosers, and fuses. They are located in the distribution substation and out on the primary and secondary feeders. These devices appear in series along a feeder so that it can sense a fault current. For permanent fault coordination, the devices operate progressively slower as one moves from the ends of the feeders toward the substation. This helps ensure the proper sectionalizing of the feeder by giving devices near feeder ends precedence to clear a fault. Such coordination ensures that only the smallest, faulted section is isolated. However, this coordination principle is often violated for temporary faults, particularly if fuse saving is employed. In such a case, a recloser attempts to clear the fault although a fuse is directly upstream from the fault location. This practice is intended to avoid blowing fuses needlessly on temporary faults because a line crew must be dispatched to replace them.

It is obvious that overcurrent protection in distribution systems involves the coordination between different levels of protective devices. Since there are many protective devices on a given distribution system, the operation of one device must be coordinated with others. Hence, there are fuse-to-fuse, recloser-to-fuse, and recloser-to-recloser coordination.

Poor coordination adversely impacts the overall power quality especially from the voltage interruption and voltage sag perspectives. For example, poor coordination between a mid-feeder recloser and downstream fuses can cause unnecessary momentary interruptions and voltage sags downstream from the recloser. It many cases poor coordination can go undetected for a long period of time until a major disruption event occurs.

1.2 Objective of Research

Based on the aforementioned background, it is desirable to have an automated system that can perform the following important tasks:

- evaluate the performance of the coordination of overcurrent protective devices (timing, sequence, and responsiveness),
- identify and correct mis-coordination between any two devices, and
- detect sympathetic tripping.

Unfortunately, there is no such automated system available even in a prototype form. Therefore, the objective of this research is to lay groundwork for developing the above mentioned automated system. In particular, our initial research effort focuses on developing an algorithm to automatically identify the most likely overcurrent protective device that operated in response to a fault event. This algorithm is an important part of the comprehensive automated system mentioned above since it can be used to verify coordination between two devices such as fuse-fuse, recloser-fuse, and recloser-recloser. For the sake of convenience and brevity, we shall call this algorithm the *identifier*.

The application and identification process of the identifier algorithm are as follows. The algorithm requires only waveform data collected from power quality monitors. They are usually installed at the beginning of the feeder or at the secondary of the transformer as shown in Figure 1-1. The algorithm will then single out voltage and current waveforms caused by short-circuit events on the same or parallel feeders. These waveforms are essentially voltage sag waveforms. Switching transient waveforms are not considered in this work since they typically do not involve overcurrent protective devices. However, it is true that some disturbance events such as inrush currents can cause an overcurrent protective device to operate. In this initial effort we are concerned only with the operation of overcurrent devices due to faults.

When a fault occurs at one of the single-phase laterals and assuming the utility does not employ a fuse saving scheme, the lateral fuse will operate if the fault is permanent. This event will be detected by all power quality monitors installed in the substation. The identifier algorithm will analyze data from all PQ monitors and determine the most likely overcurrent protective device that operated. The analysis is based on the estimated fault current magnitude seen by the protective device, the duration of the fault, and also the I^2t during the fault event. Note that the *identifier* algorithm does not require data about the feeder topology nor types of overcurrent protective devices available on the feeder. However, the availability of the later is very helpful in narrowing down the possibility of the most likely device that operated. The identifier algorithm is designed for applications in distribution feeders with and without fault saving schemes.

The *identifier* algorithm can be implemented as a stand-alone online application with access to power quality database or it can be embedded in an existing power quality database.

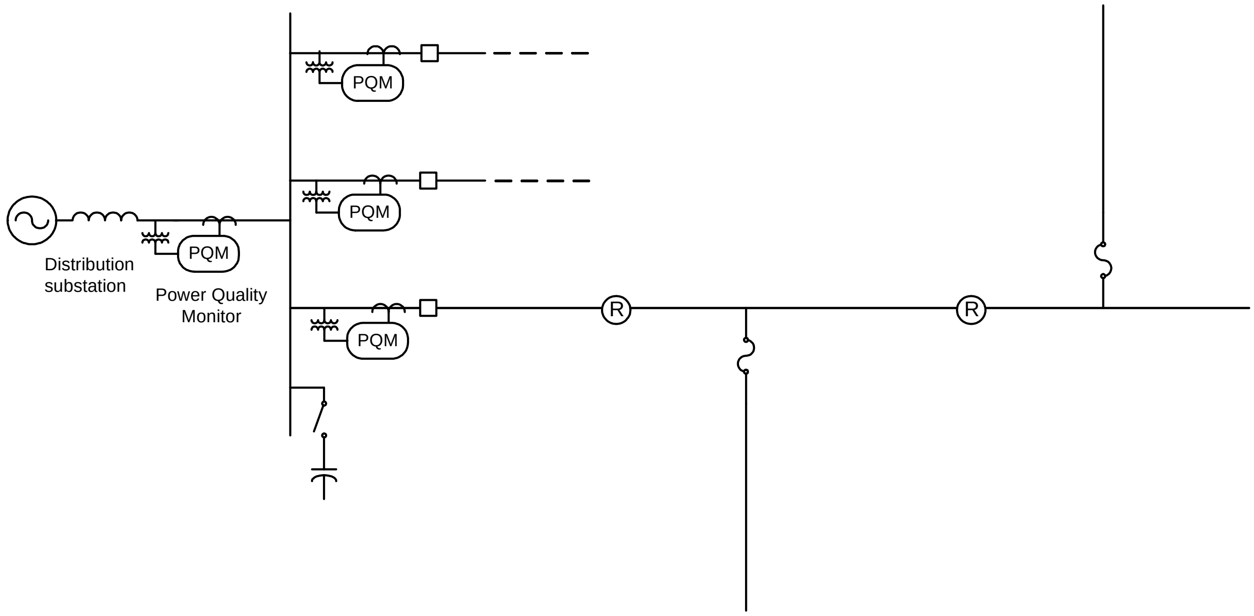

Figure 1-1
Power Quality Monitors are the Data Sources for the Identifier of Overcurrent Protective Device Operation Module

The identifier algorithm presented in this report will also be helpful in locating faults. This is obvious since the fault must be downstream from the protected device that operated. Although the algorithm, as it is now, is not intended to identify mis-coordination automatically, it can be used to help recognize poor coordination by determining if the device should have or should not have operated. Thus, this algorithm is also useful to help identify if reclosers are set incorrectly.

1.3 Overview of the Report

The organization of the report is as follows. Chapter 2 provides a brief overview of overcurrent protective devices, in particular, fuses and reclosers. The chapter describes important fuse and recloser characteristics for developing the identifier algorithm. These characteristics are fuse minimum melting and maximum clearing times, fuse I^2t energy, recloser fast and delayed time-current characteristic curves, and the reclose interval. This chapter also develops simple distribution system models to simulate the operations of fuse and recloser operations. These simulation models generate data for developing and evaluating the identifier algorithm.

Chapter 3 describes the development effort and functionality of the identifier algorithm. In particular, the identifier performs two main functions, i.e., identify the operation of reclosers and fuses. In doing so, the algorithm needs to know the utility fault clearing scheme. For a fuse saving scheme, the identifier assumes all fast events are due to recloser operations. Therefore, the identifier compares the event characteristics to recloser time-current characteristic curves. The identifier subsequently determines fuses that coordinate with the recloser. For a fuse blowing scheme, the identifier compares the event characteristics to fuse TCC curves. Methods to estimate fault current seen by a protective device and TCC curve matching are developed and presented.

Chapter 4 demonstrates the application and the performance of the identifier algorithm. There are four simulations and four real-world test cases. The results indicate that the identifier performs well.

Chapter 5 describes efforts needed to improve and expand the capability of the algorithms.

2
OVERCURRENT PROTECTIVE DEVICES IN DISTRIBUTION SYSTEMS

Overhead distribution systems are constantly affected by short-circuit conditions. When short-circuit conditions arise, a circuit interrupter operates to interrupt the fault current as quickly as possible and, in doing so, it must minimize the number of customers affected. In many cases, the circuit interrupter is a line recloser or a fuse located directly upstream to the fault. It is important to note that recloser-fuse coordination is very important for the fault-clearing process employing a fusing saving scheme. Poor coordination can cause customers downstream from the recloser to experience frequent and unnecessary short-duration interruptions [1, 2].

There are two fundamental types of short-circuits or faults on power systems:

- Temporary faults: These are due to overhead line flashover that result in no permanent damage to the system insulation. Temporary faults are caused by overgrown vegetation, animal and human contacts, unfavorable weather conditions to mention just a few. Electrical service is usually restored as soon as the fault arc is extinguished. In a radial distribution system, one circuit interrupter (i.e., a recloser or a feeder breaker with a reclosing capability) upstream from the fault location interrupts the short-circuit condition in a few cycles to a few seconds.
- Permanent faults: These are due to physical damage to some element of the insulation system that requires intervention by a line crew to repair. Permanent faults are usually cleared by an upstream fuse. The impact on end users is an outage that last from several minutes to a few hours.

This chapter provides a brief overview of most common types of overcurrent protective devices available on an overhead radial distribution system, i.e., fuses, line reclosers, and feeder breakers. Section 2.1 and 2.2 provides a brief overview of characteristics of fuses and reclosers. Note that the discussion of line and feeder breakers are integrated since it is not uncommon to find a recloser used as a feeder breaker when the available fault current is 20 kA or less. Section 2.3 and 2.4 describes the modeling of these overcurrent protective devices and the simulation of permanent and temporary fault clearing sequences.

2.1 Overcurrent Protective Devices: Fuses

The most basic overcurrent protective element on the power system is a fuse. Its primary function is to operate on permanent faults and isolate the faulted section from the sound portion of the feeder. Fuses are positioned so that the smallest practical section of the feeder is disturbed. They are low cost and maintenance free. For these reasons they are generally used in large numbers on most utility distribution systems. They are commonly used to protect individual transformers, feeder branches or laterals.

Fuses detect overcurrent conditions by melting the fuse element which generally is made of a metal such as tin or silver. This initiates some sort of arcing action that will lead to the interruption of the fault current. There are two types of fuses, expulsion and current-limiting fuses. The primary difference between the two is the way the arc is quenched. This also gives the fuses different power quality characteristics.

An expulsion fuse creates an arc inside a tube with an ablative coating. This creates high-pressure gases that expel the arc plasma and fuse remnants out the bottom of the cutout, often with a loud explosion reported to be similar to a firearm. This cools the arc such that it will not reignite after the alternating current crosses zero. The arc quenching duration can be as short as one-half of a cycle for high currents to several cycles for low fault currents. This duration also determines the duration of the voltage sag observed by loads. Due to its construction, an expulsion fuse is considerably less expensive than a current limiting fuse.

Expulsion fuses are the most commonly used type of fuses on distribution systems. The fusible element, made of either tin or silver, melts at high currents. An arc remains after the tin or silver in the fuse tube melts. The high energy arc causes a rapid pressure buildup forcing ionized gases out and prevents the arc from reigniting when the AC current crosses zero and the voltage across the opening is high. Unlike expulsion fuses, a current limiting fuse dissipates the energy in the arc in a closed environment. This is typically done by melting special sand within an insulating tube. This process actually quenches the arc very quickly, forcing the current to zero before that would naturally occur [1]. As a result of this fast quenching action, the fault can be cleared in less than 0.25 of a cycle.

In this initial research effort, the identifier algorithm can only ascertain the operation of an expulsion fuse and report the type of the fuse. Identifying the operation of fault current-limiting fuses is more complicated since the quenching duration is very short. For this reason, only expulsion fuse characteristics are described below.

2.1.1 Expulsion Fuses: Speed Ratio

The speed ratio of a fuse describes the relationship of the magnitude of the melting current at two different time instants. Thus, it is technically defined as the ratio of the magnitude of the melting current at 0.1 seconds to that at 300 seconds or 600 seconds depending on the rating of the fuse [3]. The melting current is the current at which the fuse link begins to melt. For a fuse rated 100 A and below, and above 100 A, the speed ratios are as follows, respectively:

$$\text{speed ratio (fuse} \leq 100\text{ A)} = \frac{\text{melting current at } 0.1\text{ sec}}{\text{melting current at } 300\text{ sec}}$$

$$\text{speed ratio (fuse} > 100\text{ A)} = \frac{\text{melting current at } 0.1\text{ sec}}{\text{melting current at } 600\text{ sec}}$$

A fuse with low speed ratio is relatively faster than that with high speed ratio. This is because the magnitude of the melting current at 300 seconds (or 600 seconds) is comparable to that at 0.1 seconds. Consequently, the ratio of the two quantities is small. Should the magnitude of the melting current at 300 seconds (or 600 seconds) be much smaller than that at 0.1 seconds, the ratio would be large. Therefore, fuses with a low speed ratio are relatively faster.

Based on the speed ratio characteristic, there are two types of fuses, K and T fuses. K-link fuses have a speed ratio between 6 and 8, while T-link fuses have a speed ratio between 10 and 13. Therefore, K-link fuses are relatively faster than T-link fuses [2].

2.1.2 Expulsion Fuses: Time-Current Characteristic Curves

The time-current characteristic (TCC) curves of a given fuse determine how quickly the fuse responds to different overcurrent conditions. All fuses have inverse time-current curves; thus when the current increases, the melting time decreases. Each type of expulsion fuse has two time-current characteristic curves: the minimum melt curve and the maximum total clearing curve. The minimum melt time is the quickest melting time of the fuse and is set to 90% of the average melting time of the fuse which allows for manufacturing tolerances. The total clearing time is the longest melting time of the fuse and is set to the average melting time plus the arcing time plus manufacturing tolerances. The time-current characteristic minimum melting and maximum clearing curves for 100K fuse is shown below in Figure 2-1. Note that data for TCC curves are obtained from [4].

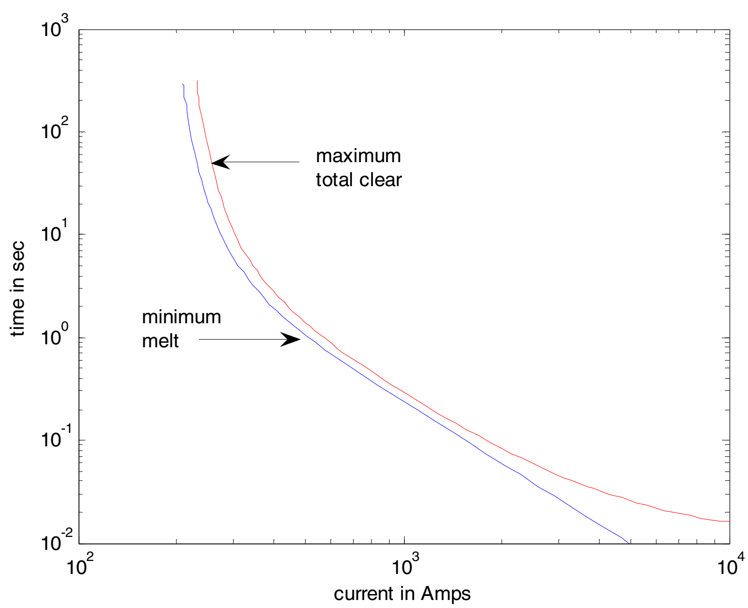

Figure 2-1
Time-Current Characteristic of a 100 A K-Link Fuse

2.1.3 Expulsion Fuses: I^2t Characteristics

The I^2t characteristic of a fuse quantifies the amount of thermal energy associated with current flow through the fuse link. The I^2t characteristic is defined as follows:

$$\text{fuse}\, I^2t = I_{RMS}^2 \times t$$

where I_{RMS} is the magnitude of the melting current in RMS, and t is the associated melting time. For fuse-fuse coordination purposes, I^2t is computed based on the minimum melting curve. Most manufacturers provide TCC curves with 0.01 seconds as the minimum melting time except for 200K, 140T, and 200T link fuses. Thus, the minimum melt I^2t for a 100K fuse is $4931.21^2 \times 0.01 = 2431$ A^2s. Table 2-1 shows the minimum melt I^2t for all K- and T-link fuses.

Table 2-1
Minimum Melt I^2t for K- and T-link Fuses

Rating, A	Min melt Current (A)		Min-melt I^2t (A2s)	
	K-link	T-link	K-link	T-link
6	230.983	385.809	534	1,488
8	320.648	526.548	1,028	2,773
10	422.988	720.066	1,789	5,185
12	548.037	938.556	3,003	8,809
15	708.637	1228.24	5,022	15,086
20	921.813	1566.09	8,497	24,526
25	1175.37	2004.88	13,815	40,195
30	1455.84	2558.92	21,195	65,481
40	1903.29	3269.33	36,225	106,885
50	2421.98	4156.13	58,660	172,734
65	2999.92	5210.03	89,995	271,444
80	3937.65	6518.11	155,051	424,858
100	4931.21	8361.06	243,168	699,073
140	7834.87	10000	613,852	1,566,700
200	10000	10000	1,490,300	3,955,100
Note: min-melt time for all fuses are 0.01 sec, except for 200 A K-link fuse (0.014903 sec), 140 A T-link fuse (0.015667 sec), and 200 A T-link fuse (0.039551sec)				

2.2 Overcurrent Protective Devices: Reclosers

A recloser is a self controlled, current sensing device that is pre-programmed to follow a sequence of tripping and reclosing operations. Its primary function is to give temporary faults opportunities to self clear, and also to save the downstream fuse if the utility employs a fuse-saving scheme. Generally, a recloser can be placed anywhere along the feeder as well as at the substation if the available fault current is less than 20 kA.

Reclosers have time-current characteristic curves similar to fuses. Instead of a melting time, the recloser has a fast operation and a delayed operation curve. During a fast operation the recloser trips and successfully recloses, allowing sufficient time for a temporary fault to clear. The delayed curve allows other protective devices to operate and isolate a permanent fault before locking out. The preset sequence for reclosers varies. Most common reclosing sequences for line reclosers (shown in Figure 2-2 [5])are as follows:

- two fast operations followed by two delayed operations, and
- one fast operation followed by three delayed operations.

The actual sequence implemented can vary since it is selected based on the historical temporary faults on the protected feeders. An example of a 'two fast operations and two delayed' operation is illustrated as follow. Once the fault current is detected the recloser trips after *n* cycles according to its TCC fast operation curve. The recloser remains open for a preset time (called the reclose interval) before reclosing. If the fault is temporary and has been cleared the recloser will remain closed, but if the fault did not clear, the recloser senses the fault current and trips again after *n* cycles according to its TCC fast operation curve. After a preset time reclose interval, the recloser will again close and sense fault current if there is any. Since the fault has not been cleared or isolated yet, the recloser remains closed for the time from its TCC delayed operation curve. This longer period allows other overcurrent system protection devices such as a downstream fuse to operate and isolate the fault, reducing the number of instantaneous and momentary interruptions that would happen if the recloser remained open. If the fault is not cleared after the recloser's fourth operation, the recloser will lockout, isolating the fault from the rest of the system.

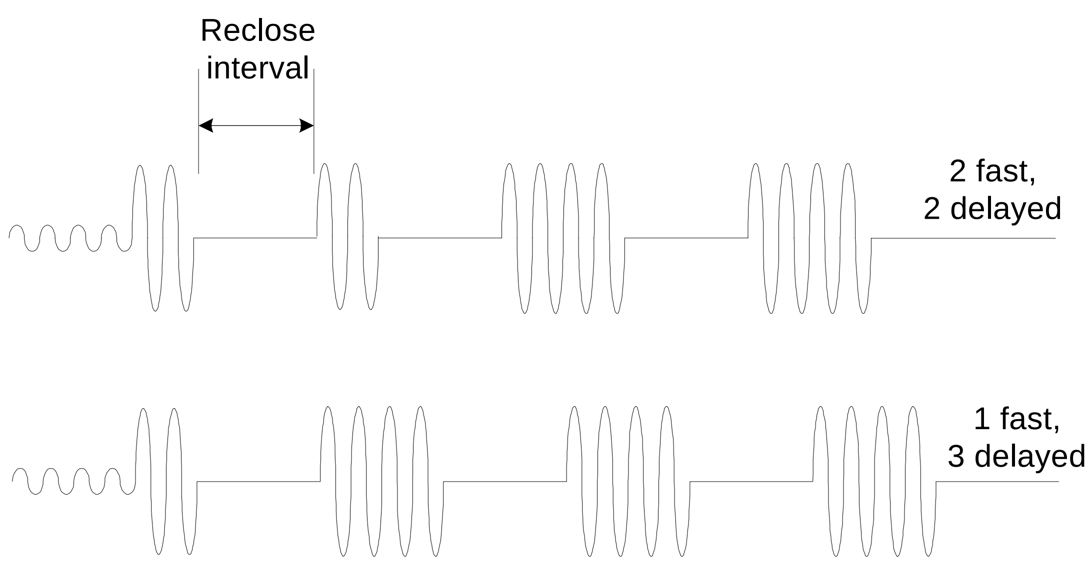

Figure 2-2
Typical Recloser Operating Sequences for Line Reclosers

The recloser curves are selected based off of continuous load current, maximum fault current at the recloser location, and minimum fault current. The recloser should have current interrupting capabilities greater than the maximum fault current at the location. A recloser rating size should be larger than the maximum continuous load current. The recloser minimum pickup current – which is twice its rated current – should be less than the minimum fault current at the end of its zone of protection. To determine if a recloser can detect the minimum fault current or that it exceeds the maximum fault current, the time current characteristic curves must be examined properly [5].

2.3 Modeling and Simulation of Fuse Protection

The availability of voltage and current waveforms from known protective device operations is critical in developing the identifier algorithm. Therefore, this section develops time-domain fuse models and simulates their operations in a distribution system. Data generated from these simulation models will be used in developing the identifier algorithm described in Chapter 3.

2.3.1 Modeling of Fuse Operation and Control

The modeling of fuse operation is carried out in PSCAD/EMTDC software package [6]. The time-domain fuse model is represented with a single-phase circuit breaker where the opening and closing time instants are determined by the fuse time-current characteristic curves. Figure 2-4 and 2-5 are used to illustrate the modeling rationale of the fuse operation.

Let a permanent fault occur downline from the 25K fuse and result in a fault current of 642 A. From the 25K TCC curves and interpolating adjacent time and current magnitude values, the minimum melting and maximum clearing times for the 642 A fault current are 0.03355 and 0.05548 seconds, respectively. The simulated clearing time can be determined by modeling the physical melting characteristics of the materials used to quench the arc. However, since our modeling purpose is to generate data for developing the identifier algorithm, the simulated clearing time (t_{sc}) is determined by averaging the minimum melting ($t_{min\text{-}melt}$)and maximum clearing ($t_{max\text{-}clear}$) times, i.e.,

$$t_{sc} = \frac{t_{min-melt} + t_{max-clear}}{2}$$

Therefore, the simulated clearing time for the fuse would be 0.04451 seconds or 3 cycles.

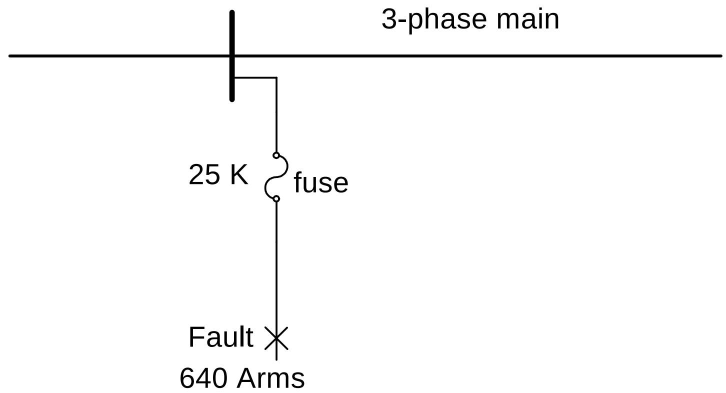

Figure 2-3
A Permanent Fault is Downstream From the 25A K-link Fuse

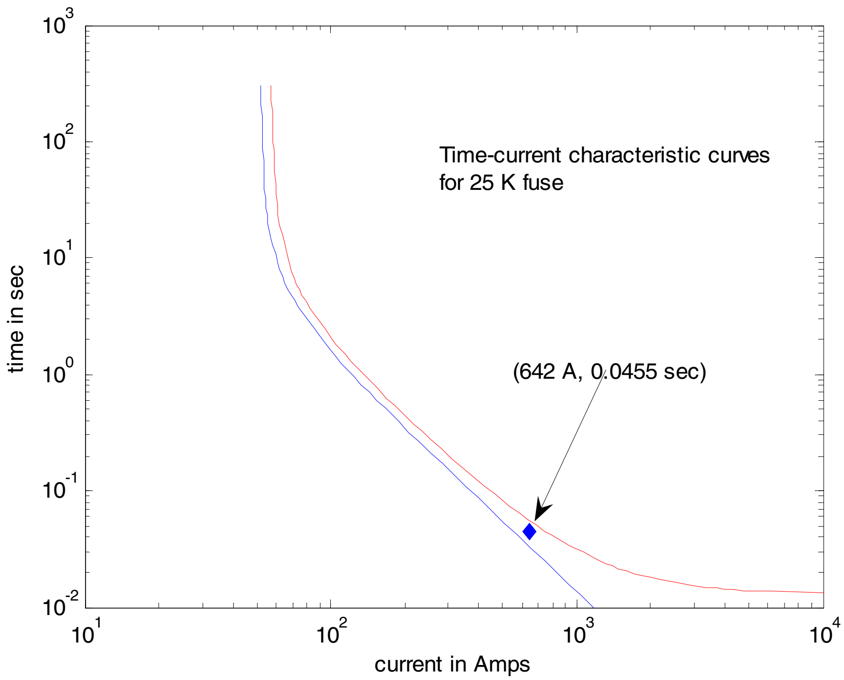

Figure 2-4
Time-Current Characteristic Curves for a 25K Fuse

The above rationale is implemented in PSCAD/EMTDC. TCC curves data must be provided and entered into PSCAD/EMTDC. It will then read off the minimum melting and maximum clearing times from the curves, and compute the fuse simulated clearing time. Figure 2-5 shows the control of the fuse clearing time.

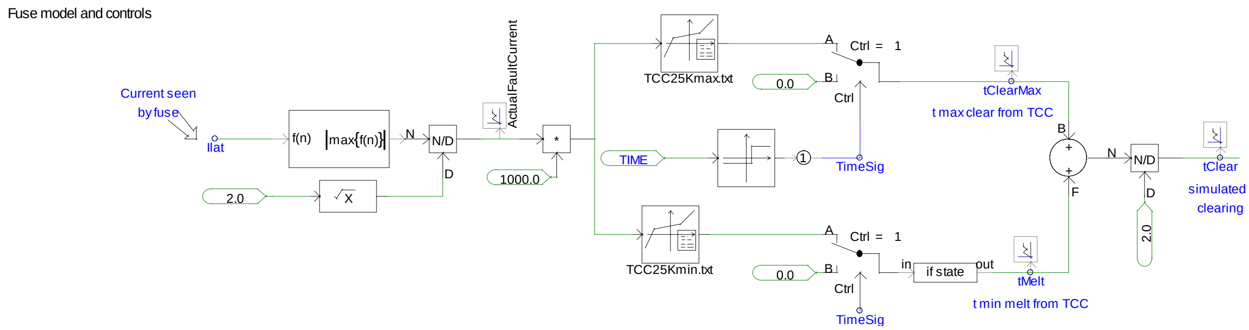

Figure 2-5
Modeling Fuse and Control Based on its Time-Current Characteristic Curves

2.3.2 Simulation of Permanent Fault Clearing Events Using Fuses

A simple distribution system model is developed to simulate fuse operations in interrupting permanent faults. The distribution system is fed by 12 MVA, 115 kV/12.47kV delta-wye-gnd connected transformer with a leakage inductance of 10%. The short circuit strength of the 115 kV system is represented with a Thevenin voltage source behind an equivalent short circuit reactance (in ohms) of

$$Z_+ = 0.16038 + j0.64151$$
$$Z_0 = 0.16977 + j0.50932$$

The distribution system consists of three radial feeders with a single-phase lateral where a 25 K fuse is used to protect it. Each distribution feeder is 10.56 x 10^3 ft long and assumed to be balanced. Thus, the overhead line is simply represented with its positive and zero sequence components (in ohms per 10^3 ft), i.e.,

$$Z_+ = 0.058 + j0.1187$$
$$Z_0 = 0.1465 + j0.3669$$

All loads in the distribution system are considered as constant PQ loads. The fuse model is implemented using the approach described above. A power quality monitor (PQ monitor) located at the secondary of the transformer records the voltage (E_{sub}) and current (I_{sub}) waveforms as illustrated in Figure 2-6 below. These voltage and current waveforms will be analyzed in the next chapter to determine which protective devices operate under fault conditions.

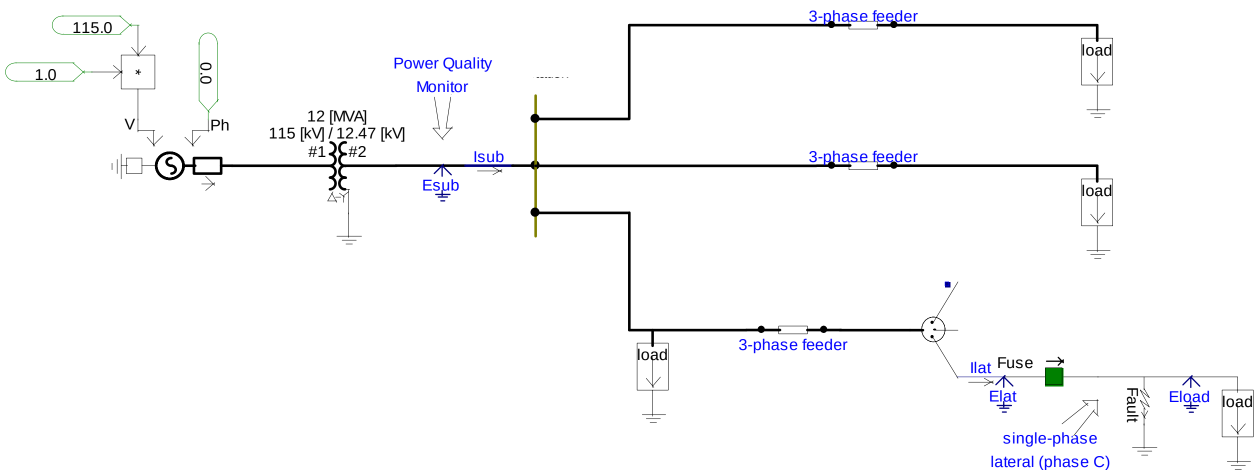

Figure 2-6
A Simple Distribution System With a Fuse Protecting the Single-Phase Lateral

In order to simulate a fuse operation, a permanent single-line to ground fault is applied downstream from the fuse (i.e., on lateral – phase C). In this example, the fault occurs at *t* = 0.225 s from the start of the simulation. Voltage and current waveforms measured by the PQ monitor are shown in Figure 2-7. It can be seen that one of the phases experiences a fault where the peak (crest) magnitude of the current is 1.53 kA. Note that this is the current seen at the substation, i.e., the totalized current which is the sum of the fault current and load current in all other feeders.

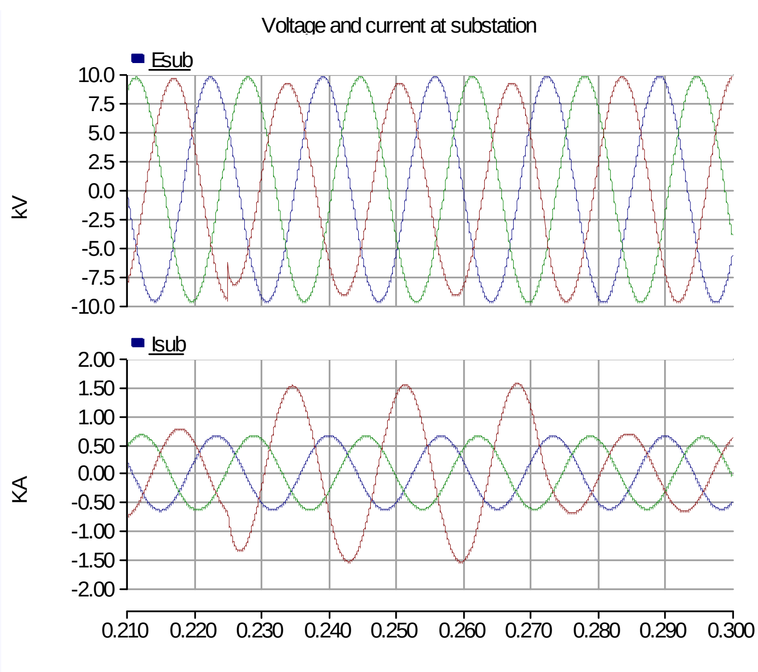

Figure 2-7
Voltage and Current Waveforms Seen by a Power Quality Monitor Located at the Substation

The fault current seen by the fuse is shown in Figure 2-8. Note the actual fault current is indeed only 900 A peak or 640 Arms. According to the TCC curves of a 25K fuse, the minimum melt and maximum clearing time (after interpolation) is between 0.03355 and 0.05548 seconds. Based on the approach presented above, the simulated clearing time is the midpoint of these two values, i.e., 0.04451 seconds. Since the fuse model is considered as an expulsion type, the actual fault clearing occurs at the next immediate current zero crossing. From the simulation, the fault is cleared within 0.047 second after the fault commences. The simulated clearing time is well within the manufacturer's minimum melting and maximum clearing times of the fuse. Therefore, the above fuse model is accurate for simulating fuse operations.

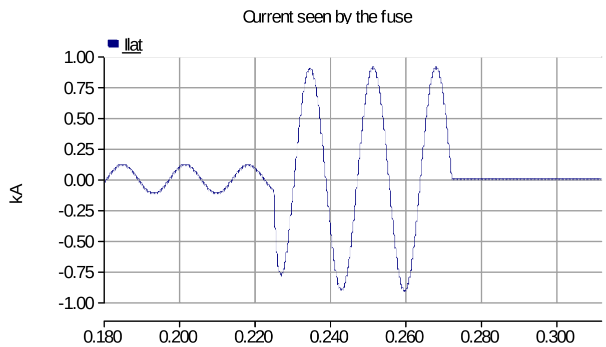

Figure 2-8
Actual Current Seen by the Fuse During a Fault Condition

2.4 Modeling and Simulation of Recloser-Fuse Coordination

For the purpose of fuse saving and interrupting temporary faults, a recloser is installed upstream from the fuses. However, recloser TCC curves must be coordinated with fuse TCC curves. Without proper coordination, a fuse may blow unnecessarily or does not operate when the fault downstream from it is permanent.

Since a recloser possesses fast and delayed curves, the recloser fast curve should be faster than the fuse minimum melting time. This would prevent the fuse from melting before the recloser operates. The coordination of the recloser and downstream fuses should also allow fuses to operate before recloser lockout for the case of a permanent fault. To prevent the recloser from locking out before a fuse can isolate a fault, the maximum clearing time of the fuse should be faster than the TCC delayed curve of the recloser. The coordination of the fuse and recloser curves should be considered for overcurrent conditions between the minimum fault current and the maximum fault current seen by the recloser.

An example of fuse and recloser selection based on their TCC curves is illustrated with a simple radial distribution feeder (see Figure 2-9) having a recloser (560 A phase pick-up, and 280 A ground pick-up) with 100T and 65T fuses. The TCC curves for the recloser and fuses are shown in Figure 2-10.

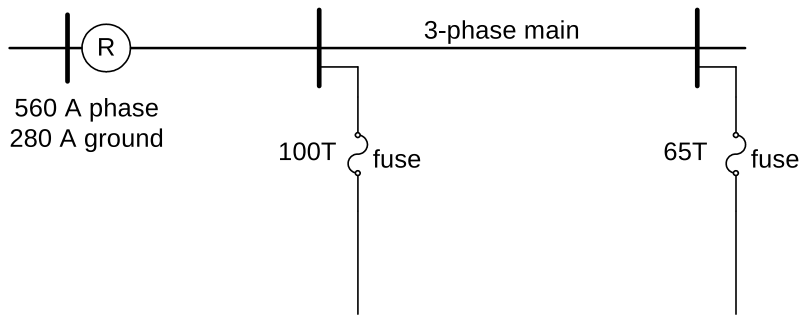

Figure 2-9
A Simple Radial Feeder With Recloser and Fuses

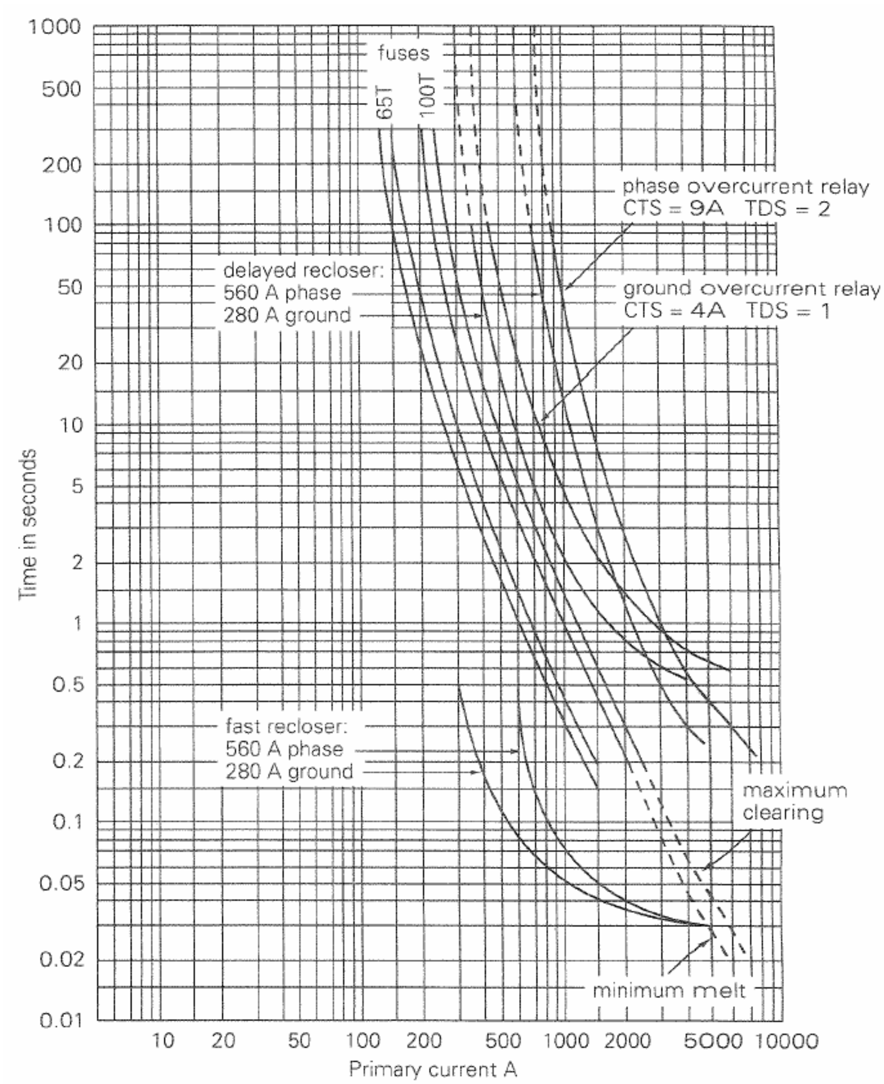

Figure 2-10
A Simple Radial Feeder With a Recloser and Fuses

2.4.1 Simulation of Recloser-Fuse Coordination for Temporary Fault Conditions

This section demonstrates proper recloser-fuse coordination in interrupting a temporary fault. The distribution feeder model is identical to that in Figure 2-6 with a recloser added to one of the feeders. The recloser has a ground and phase pick-up currents of 280 A and 560 A, respectively. To achieve proper coordination with the recloser, a 65T fuse is selected to protect the single-phase lateral. Time-current characteristic curves for both devices are shown in Figure 2-10. The distribution system is modeled in PSCAD/EMTDC and shown in Figure 2-11 below.

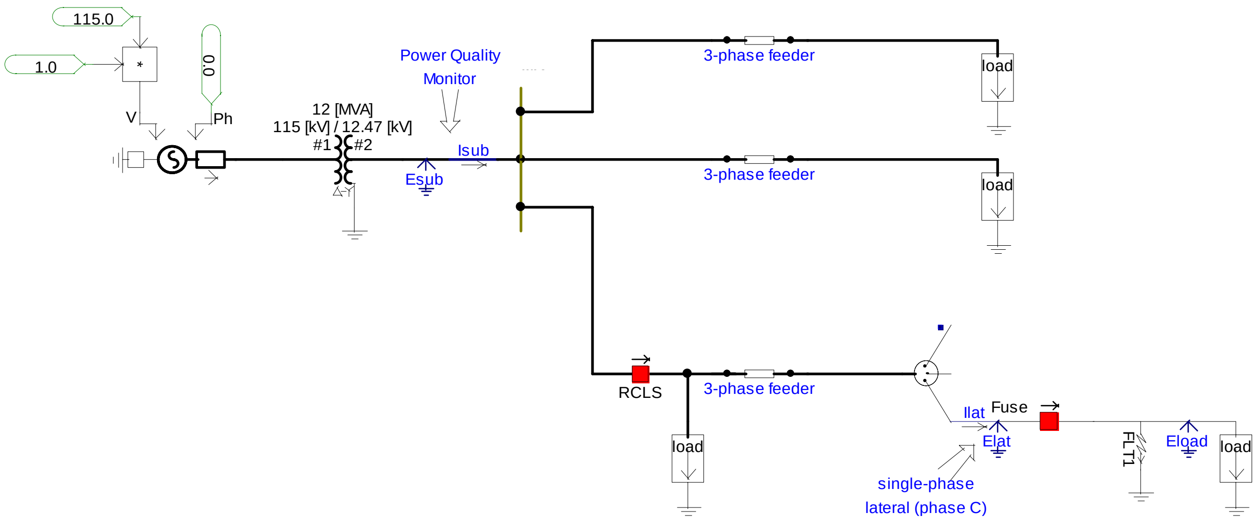

Figure 2-11
Simulation Model to Demonstrate Recloser-Fuse Coordination

Recloser and fuse operations are manually timed and controlled since automatically detecting the coordinating times for both protective devices like that for fuse operation is quite complex and beyond the scope of this project. Therefore, each recloser operation time and the fuse melting time is manually read off the device's TCC curves. The device operation times then are included in the PSCAD/EMTDC sequencer which runs when the simulation starts. Device times are unique for a specific fault condition. Should the fault condition change, a new set of device times must be prepared. The sequencer for the recloser and fuse coordination simulation is shown below in Figure 2-12.

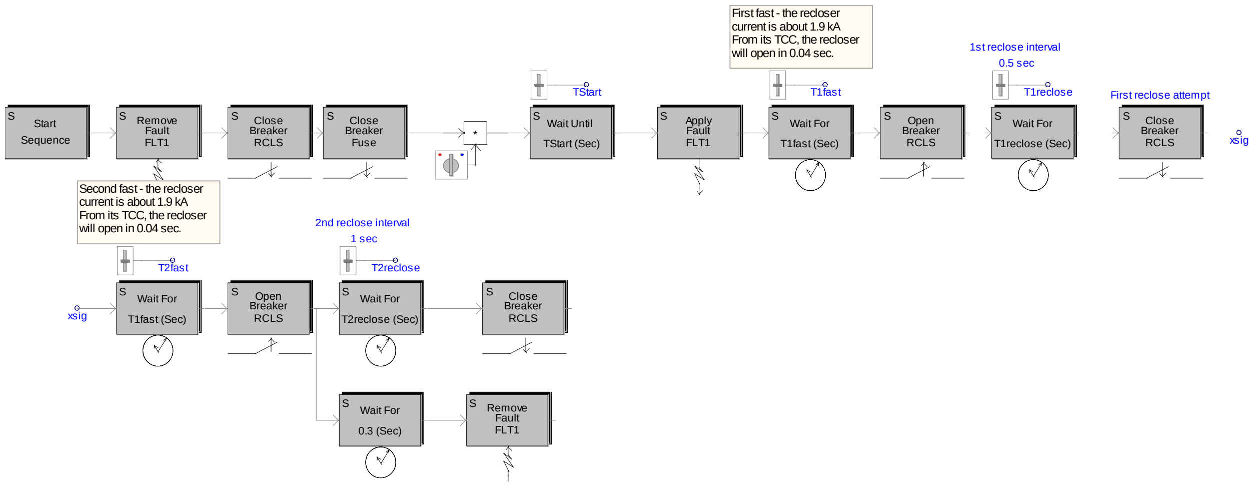

Figure 2-12
Timing and Control of Recloser-Fuse Protection Coordination for a Temporary Fault Clearing

A temporary fault with duration of 1.57 seconds is applied downstream from the 65T fuse. The distribution system is assumed to employ a fuse saving scheme. The recloser has two fast and two delayed sequences with the first recloser interval of 0.5 seconds, and subsequent intervals of 1.0 second. Voltage and current waveforms captured at the substation is shown in Figure 2-13. Note that only the faulted phase waveforms are shown. Figure 2-13 also shows the current seen by the recloser and fuse.

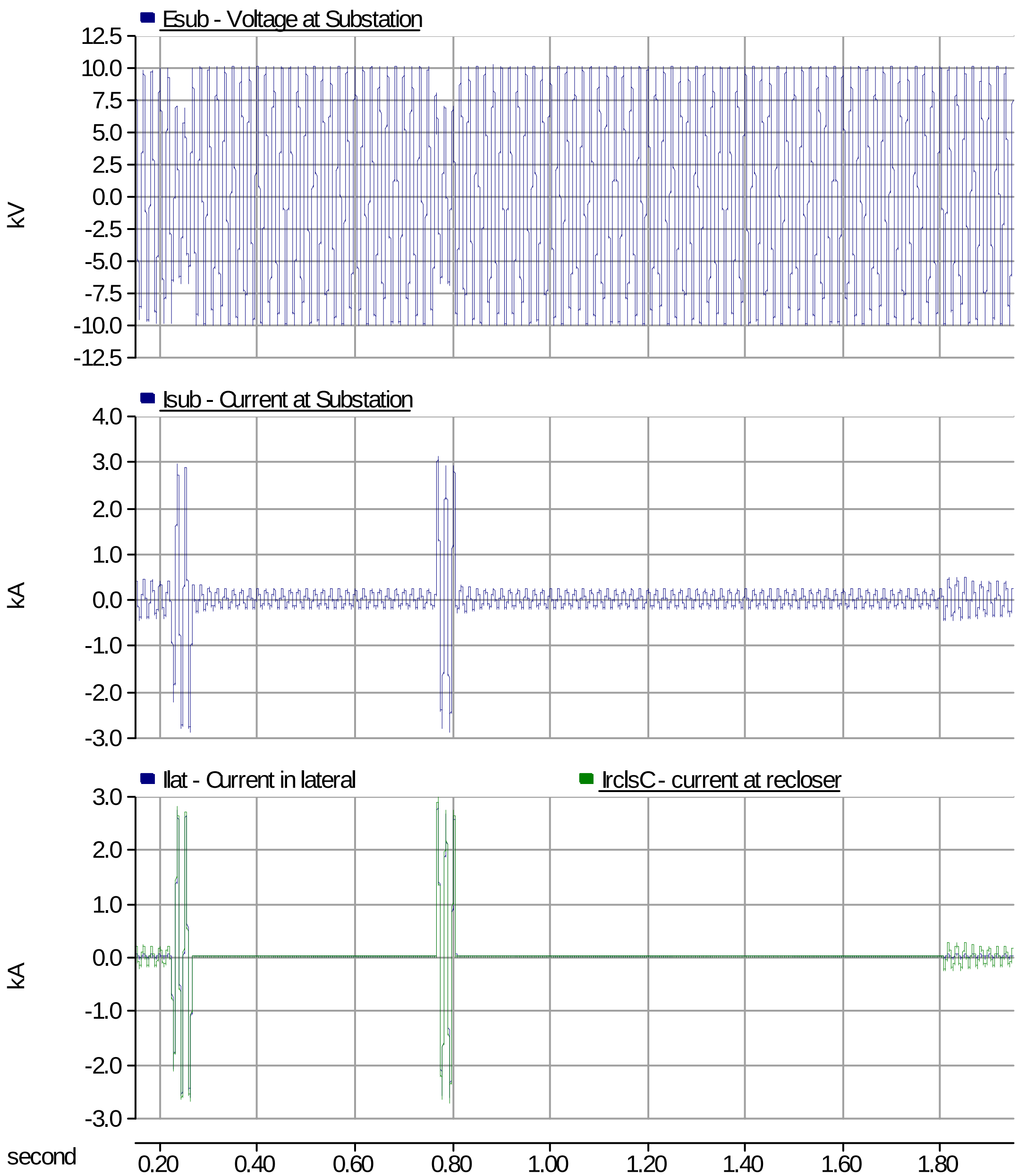

Figure 2-13
Voltage and Current Waveforms During a Temporary Fault Clearing Process

When a fault occurs, the recloser detects the fault current of about 1.90 kArms and trips after 0.04 seconds (2.5 cycles) according to its TCC (phase). This is the first recloser fast operation. The voltage waveform measured at the substation during the short-circuit condition sags to about 70% of the nominal voltage. For this level of fault current, the 65T fuse would melt after about 0.1 seconds (5 cycles). The recloser remains opened for the reclose interval period, in this case 0.5 seconds is simulated. After the reclosing interval, the recloser recloses and detects that the fault is still there and subsequently trips again after 0.04 seconds (this is the second fast operation). The second recloser interval is now extended to 1.0 second. During this time, the fault is cleared and the recloser closes back into the system. It saves the fuse from melting. Voltage and current waveforms return to nominal values after a successful clearing operation.

2.4.2 Simulation of Recloser-Fuse Coordination for Permanent Fault Conditions

Using the same approach described above, a simulation of recloser-fuse coordination for a permanent fault condition is described below. During the entire simulation, a single line to ground permanent fault is applied. Recloser and fuse activities are manually controlled using the sequencer. Figure 2-15 shows voltage and current waveforms seen at the substation, fuse, and recloser. The sequence of events is described below.

Let a single-line to ground fault occurs at 0.225 seconds following the start of the simulation. The recloser detects current with a magnitude of 1.90 kArms. According to the recloser TCC curves (phase), it opens after 0.04 seconds (2.5 cycles). This is the first fast operation. Note that the recloser status is 0 when it is closed; and 1 when it is open. While the reclose had not opened, the current measured at the substation was very high indicating a downstream fault condition.

The recloser recloses after its first recloser interval of 0.5 seconds. Since it is a permanent fault, the fault is still present and the recloser subsequently trips after 0.04 seconds (second fast operation). The second recloser interval is 1.0 second. Since there have been two fast operations, the recloser switches to a delayed curve. The recloser now stays close for about 0.95 seconds. During this duration, the downstream fuse (65T) melts since the maximum clearing time is 0.10 seconds (5 cycles). The permanent fault is now isolated. Customer downstream from it will have no electrical service.

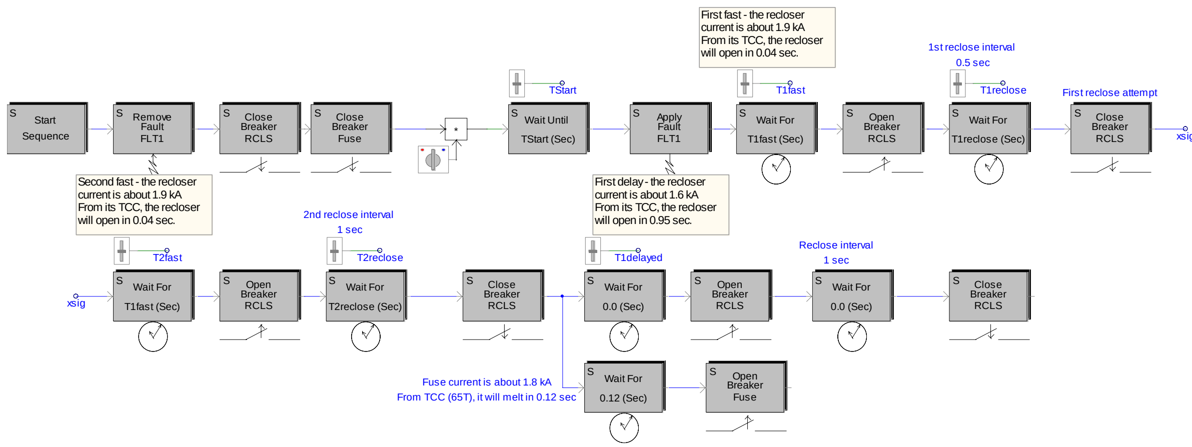

Figure 2-14
Timing and Control of Recloser-Fuse Protection Coordination for a Permanent Fault Clearing

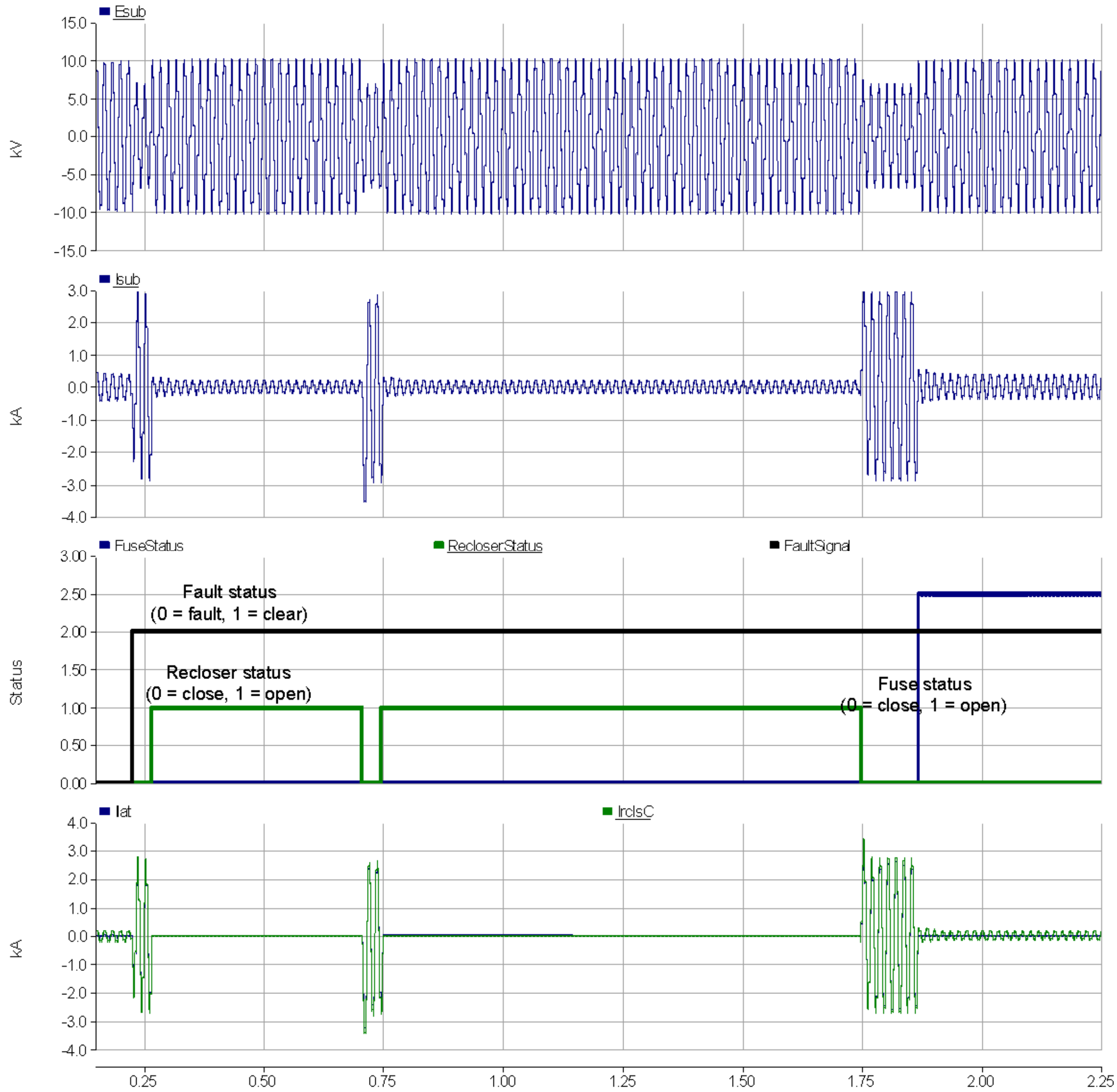

Figure 2-15
Voltage and Current Waveforms During a Permanent Fault Clearing Process

3

AUTOMATED ALGORITHM FOR IDENTIFYING THE OPERATION OF PROTECTIVE DEVICES

3.1 Overview of Algorithm Functionality

When a fault occurs on a distribution system, the current flowing in the feeder exceeds its nominal magnitude and can cause damage if it is not immediately cleared. A variety of protective devices can be used to limit the damage. These devices include reclosers and fuses on a radial distribution system. To ensure the highest degree of reliability, these devices must be coordinated. Ideally, there should be an automatic system for evaluating the performance of the coordination of protective devices on a radial system.

This chapter describes the methodology for developing and implementing the proposed automated system to identify which protective device operated to clear a short-circuit condition. As mentioned in Chapter 1, for the sake of convenience and brevity, we shall simply call this algorithm as the identifier algorithm. As a matter of fact, the proposed identifier can also be used to verify the recloser-fuse coordination. Note that due to the budget constraint, the initial work focuses on identifying expulsion fuse and line recloser operations.

Figure 3-1 illustrates the overall algorithm functionality, inputs of the algorithm, and the intended outputs. The algorithm input requirements are as follows:

- Three-phase voltage and current waveforms, preferably those measured at the beginning of the feeder since it will provide a better estimate of the fault current seen by the protective device. However, those measured at the secondary of the substation transformer, i.e., totalized current and voltage, are acceptable as well.
- Time-current characteristic curves of all protective devices used on the distribution system. This data set is indeed optional. When the data are not available; the algorithm will assume that the distribution system employs most common types of reclosers, and K and T fuses. The algorithm ideally has access to a database containing recloser and fuse TCCs.
- Utility fault clearing practices, i.e., fuse saving or fuse blowing. Since the proposed algorithm treats each disturbance event as an independent event, this input helps identify a recloser or a fuse operation.

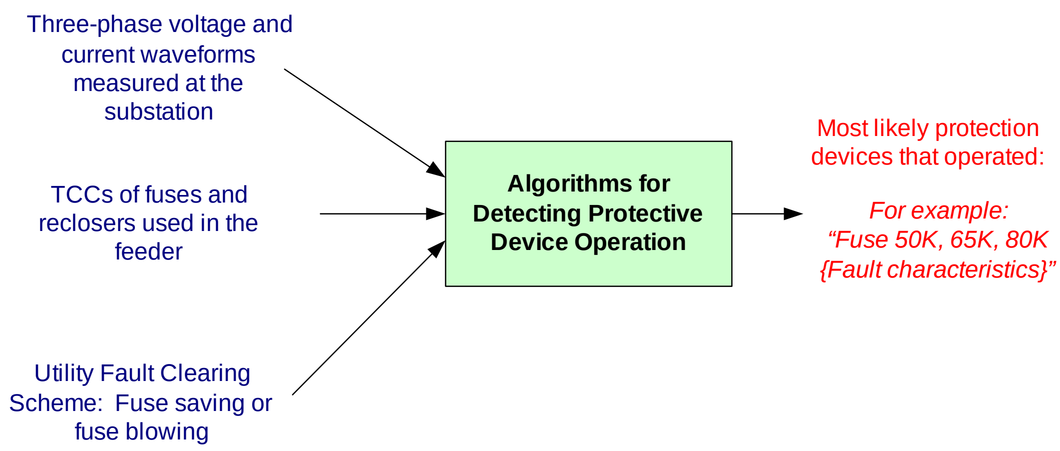

Figure 3-1
Input and Output Requirements for the Identifier Algorithm

Given the above input data, the algorithm will be designed to perform the following key functions:

1. Since there are numerous types of power quality events captured by the power quality monitor, the algorithm will ideally single out events that are caused by fault conditions. Most of these events are voltage sag and instantaneous or momentary interruption events. In developing the identifier algorithm, we assume that there will be a separate algorithm to select events caused by fault conditions. Thus, the identifier algorithm initial task would be to verify and determine if a fault were indeed present in the three-phase voltage and current waveforms.

2. Since the given voltage and current waveforms are not measured at the protective device, the identifier algorithm must perform the following estimation:

   - The algorithm estimates the fault current magnitude seen by the protective device.
   - The algorithm estimates the duration during which the fault current flows in the device. For the sake of brevity, let us designate these two parameters as the fault magnitude and the fault duration. The latter is indeed a misnomer since it is not the duration of the fault; rather it is the duration during which the fault flows in the device.
   - Based on the fault current magnitude and duration, the algorithm computes the I^2t characteristic of the fault event.

3. The algorithm then identifies the operation of the protective device as follows:

   - For a fuse-saving scheme: Since it is a fuse saving scheme, the first event must be due to a recloser operation. The algorithm determines which reclosers can operate, and subsequently identifies fuses that coordinate well with the recloser. This can be done by comparing recloser and fuse TCC curves to the fault magnitude and duration.
   - For a fuse-blowing scheme, the algorithm determines which fuses can operate to clear a fault by comparing the fault magnitude and duration to fuse TCC curves, and by comparing the empirical I^2t to the manufacturer's minimum I^2t of the fuses used in the distribution system.

Outputs of the identifier algorithm are: the fault current magnitude in RMS, the voltage sag in RMS, the phase where the fault is present, the fault duration, the identified protective devices and a plot of their TCC curves. Table 3-1 and Figure 3-2 provides a summary of functions and components of the automated protective device detection system.

Table 3-1
Functional Specification Summary of the Proposed Algorithm

Sub-Modules	Functions	Outputs	Data Requirement
Fault Existence	To determine if fault conditions are present in measured voltage and current waveforms	Phase of fault, Voltage, Current	Measured Voltage and Current Waveforms
Fault Extracting Characteristics	Extracting Fault characteristics from voltage and current waveforms	Magnitude of Voltage sag, Fault current magnitude, and duration of fault	Voltage and Current waveforms
Fuse Blowing Scheme	To determine which fuses match the fault signatures extracted, by comparing fault characteristics and the I^2t calculated to the device's TCC and I^2t of devices provided.	Fuse type	Magnitude of fault current, duration of fault, and type of fuses on user's system.
Fuse Saving Scheme	To determine which recloser matches the extracted fault signatures and identify fuses that coordinate with the recloser.	Fuses that coordinate with the recloser	Fault Magnitude, the fast operation time of recloser, list of reclosers on user's system
Display	To display the results of the algorithm	Fault Magnitude in RMS, Voltage Sag in RMS, duration of fault, TCC plots of devices identified with the fault current	Devices Identified, Fault Magnitude in RMS, Voltage Sag in RMS, duration of fault

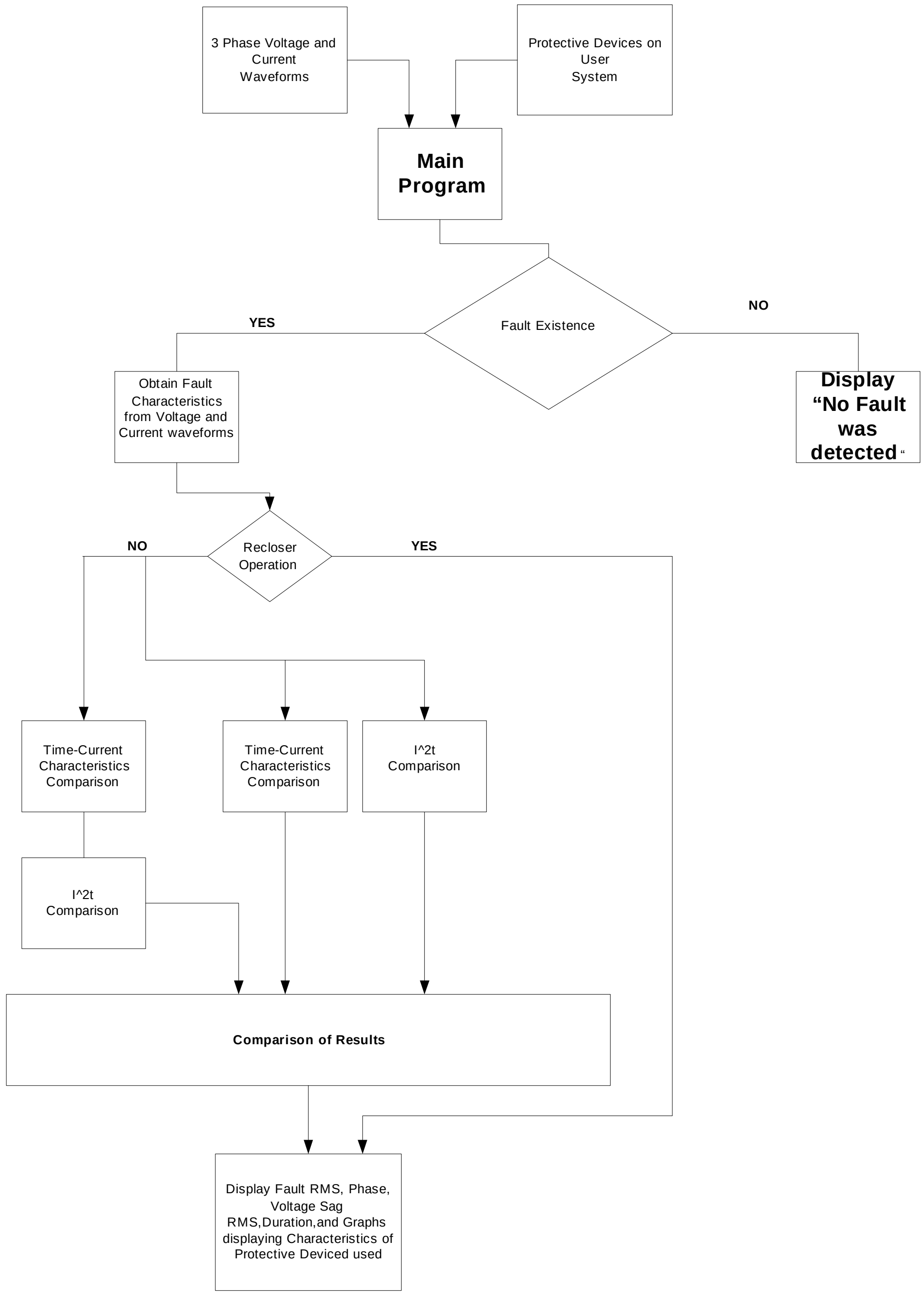

Figure 3-2
Flow Chart Description of Automated Algorithm for Detection System

3.2 Development of the Fault Detection and Verification Module

The primary function of this module is to verify and determine that a given three-phase voltage and current waveforms is caused by a fault downstream from the monitoring location. In this work, we assume that a fault event occurs when the following two conditions are satisfied:

- The magnitude of the voltage waveforms drops to 90% or below for one or more cycles. The fault can involve more than one phase.
- The magnitude of the current waveform is 150% or more of the pre-fault current, i.e., the load current. In the algorithm implementation, the 150% threshold is hard-coded. It is intended to minimize the number of inputs that have to be keyed in. However, it can be made as a variable. A 150% value is selected so that it detects fault conditions with low current magnitudes. Unfortunately, due to this low threshold the algorithm may produce an incorrect result.

Based on these criteria, we will determine the number and magnitude of voltage and current waveform crests. These parameters are then used to determine if the event is caused by a short-circuit condition and the faulted phases.

Typical voltage and current waveforms due to a fault condition is shown in Figure 3-3. These waveforms are generated using PSCAD/EMTDC. Note that all voltage and current waveforms used in this work are set to have sampling rates of 256 and 128 points/cycle, respectively, with a total data length of six to seven cycles. The choice of sampling rate and data length is intended to mimic actual data collected from power quality monitors.

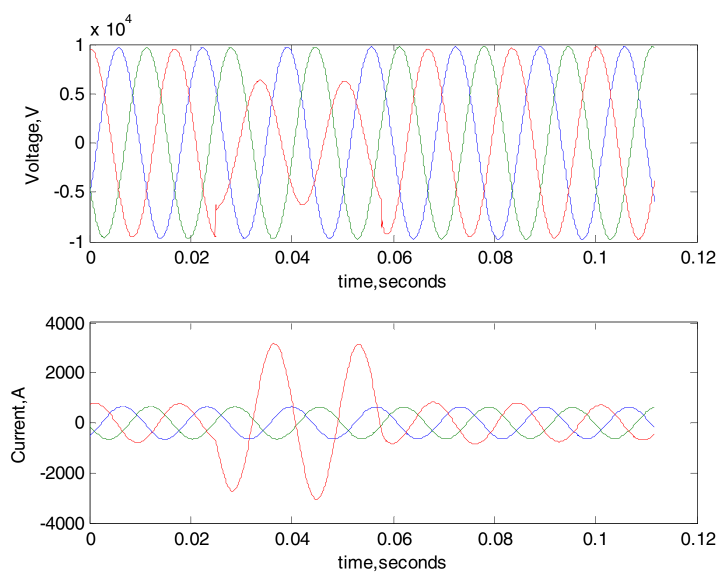

Figure 3-3
Three-Phase Voltage and Current Waveforms Due to a Short-Circuit Event

3.2.1 Locating Crests and Magnitudes of a Waveform

The number of waveform crests (or peaks) and magnitudes are estimated by sweeping the waveform from the beginning to end, and determines the local maxima and minima. Unfortunately, this approach has pitfalls in that it may miss the first and last positive or negative crest when the crest is located very close to the beginning or end of the waveform. Using voltage and current waveforms shown in Figure 3-4, the positive and negative crest magnitudes of the faulted voltage and current waveforms are shown in Table 3-2 and 3-4, respectively.

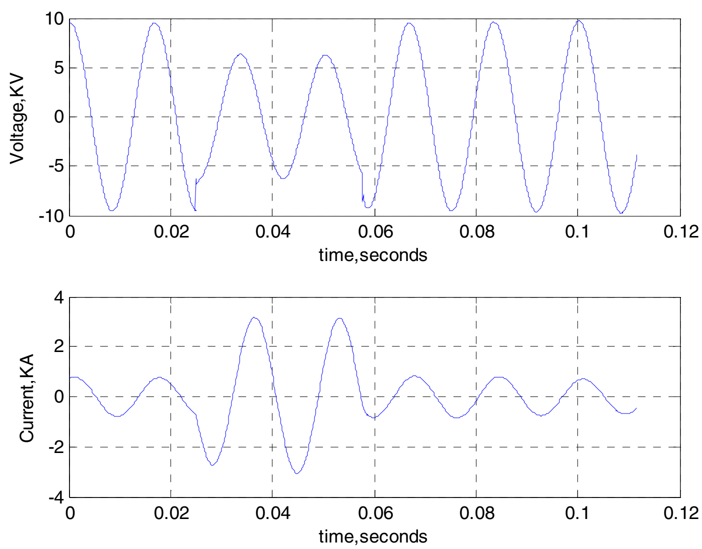

Figure 3-4
Voltage and Current Waveforms Involved in a Short-Circuit Event

Table 3-2
Voltage Positive and Negative Crest Magnitudes

Positive Crest Values(KVcrest)	Negative Crest Values(KVcrest)
9.56	-9.54
9.56	-9.53
6.37	-6.27
6.28	-9.27
9.56	-9.57
9.59	-9.57

Table 3-3
Current Positive and Negative Crest Magnitudes

Positive Peak Values(KAcrest)	Negative Peak Values(KAcrest)
0.769	-0.708
0.769	-2.72
3.17	-3.06
3.13	-0.824
0.803	-0.841
0.810	-0.841
0.810	-0.841

3.2.2 Estimating No-Fault Steady-State Current and Voltage Magnitudes

Given the voltage and current crest magnitudes, it is possible to estimate the corresponding voltage and current magnitudes during a no fault condition. The estimation is done by averaging the median values of positive and negative crest magnitudes, i.e.,

$$V_{no-fault\ crest} = \frac{\text{median[positive crest voltages]} + \text{median[}|\text{negative crest voltages}|\text{]}}{2}$$

$$I_{no-fault\ crest} = \frac{\text{median[positive crest currents]} + \text{median[}|\text{negative crest currents}|\text{]}}{2}.$$

Using the examples presented in Tables 3-2 and 3-3, no-fault voltage and current crest magnitudes are:

$$V_{no-fault\ crest} = 9.5475\,kVcrest = 6.75\,kVrms \text{ and,}$$

$$I_{no-fault\ crest} = 0.8255\,kAcrest = 0.5837\,kArms.$$

3.2.3 Verifying a Fault Condition

With the estimates of no-fault voltage and current crest magnitudes, the root cause of the waveform can be verified as follows.

- Each crest value is compared to that of no-fault crest.
- For a voltage waveform, if the crest value is less than 90% of the no-fault voltage crest magnitude $V_{no\text{-}faultcrest}$, and the number of such instances is two or more, the voltage waveform was caused by a short-circuit condition. A threshold of two instances (one complete cycle) is needed since most fuses have a minimum melting time of 0.01 seconds, which corresponds to 0.6 cycles. Furthermore, two instances provide additional confidence in the estimate.

- Similarly, for a current waveform, if the crest value is more than 150% of the no-fault current crest magnitude $I_{no\text{-}faultcrest}$, and the number of such instances is two or more, the current waveform was involved in a short-circuit condition downstream from the monitoring location.

Results for voltage and current waveforms from the same phase must not differ by more than one instance. Should the results conflict with one another, the verification cannot be made. Using the above example, the voltage waveform has three instances where its crest voltages are less than or equal to 90% of $V_{fault\ crest}$, i.e., 6.37, 6.28, and 6.27 kVcrest. The average crest value for these three instances is 6.307 kVcrest (4.46 kVrms). Similarly, for the current waveform there are four instances where its crest currents are 150% $I_{fault\ crest}$ or larger, i.e., 3.17, 3.13, 2.72, 3.06 kAcrest. The average crest value for these instances is $I_{TotalRMS@substation}$ = 3.02 kAcrest (2.14 kArms). Note that this current is the total current seen at the substation. Based on this analysis, it is verified that phase C is involved in a short-circuit condition which is in agreement with the simulation model.

3.2.4 Estimating Fault Duration Seen by the Protective Device

The duration of the fault can be simply determined by averaging the total number of positive and negative crests in the voltage and current waveforms that satisfy the fault condition criteria. Alternatively, it can also be determined using the wavelet transform [7]. Using the above example, the fault duration experienced by the protective device $t_{fault\text{-}empirical}$ is 2.0 cycles or 0.0417 seconds.

3.3 Estimating I^2t and Fault Current Magnitude Seen by the Protective Device

A protective device operates based on the magnitude of the current it sees. However, it is impossible to measure this quantity directly. Instead, the current seen by the protective device must be estimated based on the current measurement taken at the substation. We employed two methods to estimate the current magnitude seen by the protective device. Fault current estimates from both methods are then averaged to provide a better accuracy.

3.3.1 Direct Subtraction Method

The direct subtraction method assumes that the load current contribution does not change during the fault. Therefore, the total current measured at the substation is

$$I_{TotalRMS@substation} = I_{FaultRMS} + I_{LoadRMS}$$

Solving for the fault current leads to

$$\hat{I}_{FaultRMS1} = I_{TotalRMS@substation} - I_{LoadRMS}$$

The fault current estimate for the example given above is

$$\hat{I}_{FaultRMS1} = 2.14 - 0.583 = 1.55 \text{ kArms}$$

Figure 3-5 illustrates sections of the waveform that contain load and fault currents, and no-fault current.

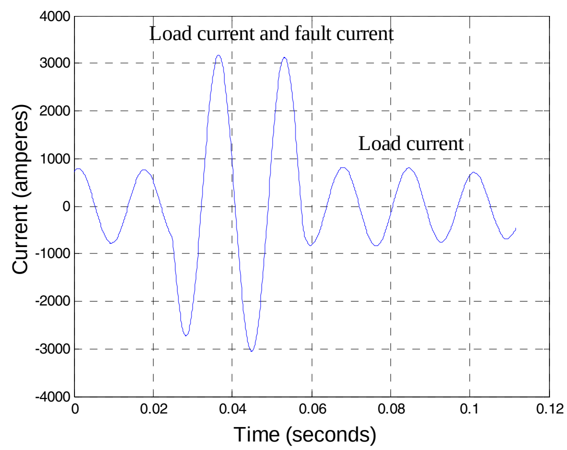

Figure 3-5
Estimating the Magnitude of Fault Current Seen by the Protective Device

3.3.2 Constant Load Current and Impedance Method

An alternative method for estimating the fault current seen by the protective device assumes that the load possesses a constant impedance characteristic, and it is in parallel with the fault impedance. Furthermore, it also assumes that the load current does not change during the fault condition. Figure 3-6 illustrates these assumptions.

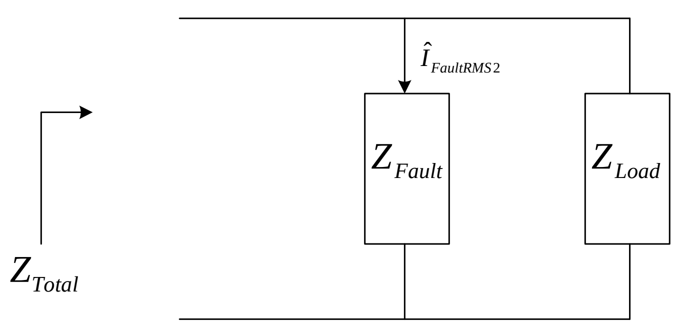

Figure 3-6
Load and Fault Impedances are Assumed in Parallel in Estimating the Magnitude of Fault Current Seen by the Protective Device

The estimation steps are as follows.

1. The first step computes voltage and current magnitudes before and during the fault condition. The algorithm extracts portions of the waveform and perform a Fourier analysis to determine the fundamental frequency phasor quantities (in RMS), i.e.,

$$V_{PreFault} = 6.72 \text{ - } j0.616 \text{ kV}$$

$$V_{DuringFault} = \text{-}4.57 \text{ - } 0.172 \text{ kV}$$

$$I_{PreFault} = 0.505 \text{ - } j0.24 \text{ kA}$$

$$I_{DuringFault} = \text{-}0.693 + j2.13 \text{ kA}$$

2. Load impedance can be estimated using quantities before the fault occurs, i.e.,

$$Z_{Load} = \frac{V_{PreFault}}{I_{PreFault}} = \frac{6.72 - j0.616\,j}{0.505 - j0.24\,j} = 11.32 + j4.15 \text{ ohms}$$

3. The total impedance during the fault is the parallel combination of the load and fault impedances, thus,

$$Z_{Total} = \frac{V_{DuringFault}}{I_{DuringFault}} = 0.5575 + j1.9642 \text{ ohms}$$

4. Based on Z_{load} and Z_{total} quantities, Z_{fault} can be computed using the above assumption, i.e.,

$$Z_{Fault} = \frac{1}{\frac{1}{Z_{Total}} - \frac{1}{Z_{Load}}} = 0.2809 + j2.23 \text{ ohms}$$

5. Finally, the fault current seen by the protective device is estimated as follows:

$$\hat{I}_{FaultRMS2} = \frac{V_{DuringFault}}{Z_{Fault}} = 2.04 \text{ kA}$$

Fault current estimates from these two approaches are then averaged, thus the estimated fault current is $\hat{I}_{FaultRMS} = 1.80$ kA. The actual fault current from the simulation is 2.0 kA.

3.3.3 Estimating Empirical I^2t of a Protective Device

The I^2t characteristic of a fuse is very useful to estimate whether the fuse has melted. It quantifies the amount of thermal energy associated with the current flowing through the fuse link. The I^2t magnitude can be determined by the product of the square of the estimated fault current and the time during which the fault passes through the fuse, i.e.,

$$fuse\ I^2t_{empirical} = \hat{I}^2{}_{FaultRMS} \times t_{fault-empirical}\ .$$

Using the example presented above, the I^2t value would be 162.6×10^3 A^2s.

3.4 Identifying Recloser Operations

As mentioned in Chapter 2, a fuse saving scheme is a practice to prevent unnecessary melting of a fuse during a fault clearing operation. A recloser located upstream from the fuse can prevent the fuse from melting. For a temporary fault, a recloser operates to clear the fault and prevent fuses located downstream from melting. If a fault is permanent, the fuse should melt to isolate the fault from the rest of the system. The fuse saving scheme works only if the fuse and the recloser are properly coordinated.

This module identifies which reclosers operated to clear a fault and identifies fuses that can coordinate with the recloser. The identification of recloser and fuse operations are done as follows:

1. Compare the estimated fault magnitude and duration determined from the voltage and current waveforms to the TCC curves of the recloser.
2. With the recloser identified, the fuses downstream from the recloser are determined by comparing the estimated fault magnitude and duration to TCC curves of fuses used in the distribution feeder.

A PSCAD/EMTDC model is used to simulate a fuse saving system and generate the voltage and current waveforms. In order to create accurate data a complete fault clearing operation was simulated. This corresponds to two fast and two delayed operations of a recloser. The length of the waveforms for the entire clearing operation can take a few seconds. The total operation sequence is captured by a power quality monitor as several independent disturbance events since most PQ monitors are limited to capturing seven cycles of data at a time. Figure 3-7 shows an example of a successful first fast operation of a recloser.

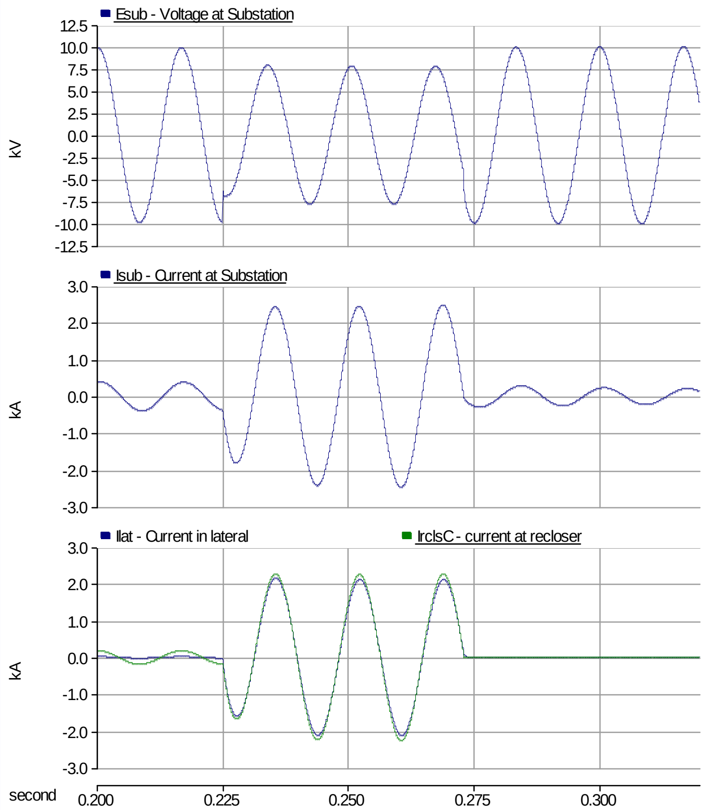

Figure 3-7
First Fast Operation of a Recloser

Independent events must ideally be correlated so as to determine whether the fault is permanent and which fuses can operate if the fault is permanent. The algorithm subsequently evaluates the recloser-fuse coordination and the timing of the sequence. Unfortunately, due to the budget constraint, we only analyze the first and second fast events in which the recloser operates to clear the fault. Note that we have assumed that the utility employs a fuse saving scheme, therefore, the first or second fast event must be due to the recloser operation. The algorithm then matches the empirical fault signatures to recloser TCC curves. It is possible though that the recloser fails to operate, thus forcing the fuse to isolate the fault condition. However such scenarios are reserved for future work.

Our proposed algorithm will determine which recloser operates based on the TCC comparison and reports fuses that can be properly coordinated with the recloser. Table 3-4 provides the functional specification while Figure 3-8 illustrates the analysis procedure of the fuse saving module.

Table 3-4
Functional Specification of Fuse Saving Module

Sub-Modules	Functions	Outputs	Data Requirement
Recloser Operation	Determine which recloser operated	Recloser, Derived Fast Time, Derived Delay Time	Fault Magnitude, sensing time (fault duration)
Recloser to Fuse Coordination	Determine which fuses coordinate with the identified recloser	Recloser and Fuses	TCC data for specified fuses, Derived Fast Time, Derived Delay Time

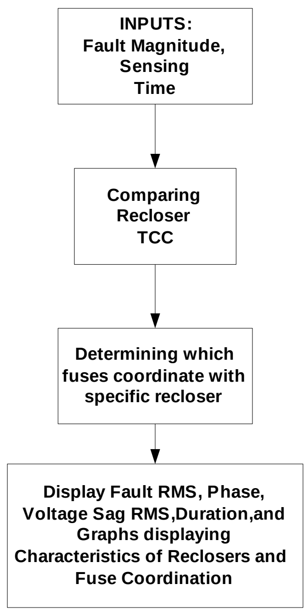

Figure 3-8
Analysis Procedure for Identifying a Recloser Operation

3.4.1 Identifying Recloser Operations Using TCC Curves

Identification of recloser operations is carried out by comparing how close the fault current and duration point , i.e., the ‘*empirical point*’ $\left(\hat{I}_{FaultRMS}, t_{fault-empirical}\right)$ to the TCC curves under investigation. Note that the fault magnitude and duration $\left(\hat{I}_{FaultRMS}, t_{fault-empirical}\right)$ are estimated using the procedure describes in Section 3.2 and 3.3.

The comparison is done by determining the time corresponding to the fault magnitude $\hat{I}_{FaultRMS}$ on the fast TCC curve using a polynomial interpolation technique. Let this time be $t_{derive\text{-}rec\text{-}fast}$. Note that the '*derived point*' must be on the fast TCC curve since $t_{derive\text{-}rec\text{-}fast}$ is obtained from the TCC fast curve through interpolation. These two points are illustrated in Figure 3-9. The time difference indicates how close the empirical point to the TCC curve, i.e.,

$$\Delta t_{recloser-fast} = \left| t_{fault-empirical} - t_{derive-rec-fast} \right| .$$

The time difference $\Delta t_{recloser-fast}$ is computed for all recloser TCC curves. Note that in this work we limit the number of reclosers to only 560 amps and 280 amps phase and ground reclosers. The smallest time difference indicates a match, i.e., the recloser whose TCC curve produces the smallest time difference operates.

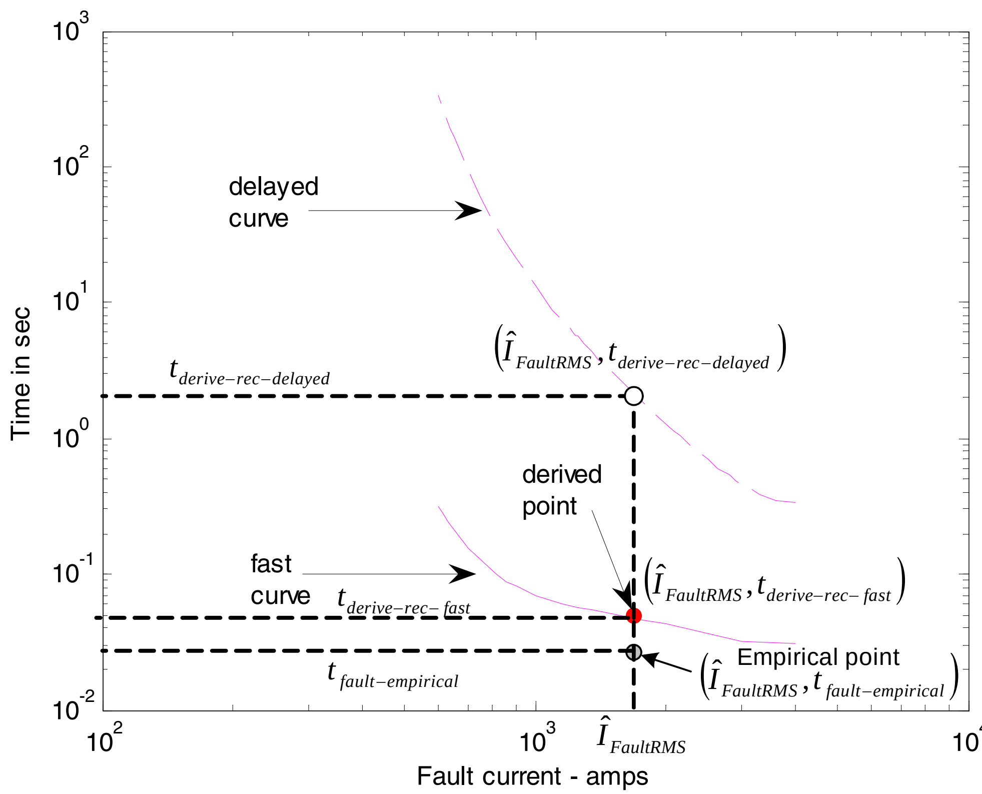

Figure 3-9
Estimating Various Times on Recloser TCC Curves

Now that the recloser has been identified, the delayed time of the recloser can be determined using the recloser TCC delayed curve. Let this time be $t_{derive-rec-delayed}$. It corresponds to the delayed time so that a downstream fuse can melt to clear a permanent fault in the system. The delayed time $t_{derive-rec-delayed}$ is also determined by using a polynomial interpolation technique.

3.4.2 Identifying Downstream Fuses That Coordinate the Recloser

Based on the identified recloser, fuses that can be coordinated with the recloser are determined. Fuse TCC curves must be located between the recloser fast and delayed TCC curves as illustrated in Figure 3-10.

Since the recloser has been identified, the derived and empirical points must be very close if not line up almost exactly. For this reason, we will assume that $t_{derive\text{-}rec\text{-}fast}$ is nearly identical with $t_{fault\text{-}empirical}$. Times on fuse TCC minimum melting and maximum clearing curves can be computed based on $\hat{I}_{FaultRMS}$ using a polynomial interpolation technique. Let these times be $t_{derive\text{-}fuse\text{-}min\text{-}clear}$ and $t_{derive\text{-}fuse\text{-}max\text{-}clear,}$ respectively. These two times must between reclosers fast and slow times, i.e.,

$$t_{derive-rec-fast} \leq t_{derive-fuse-melt} \leq t_{derive-rec-delayed}$$

$$t_{derive-rec-fast} \leq t_{derive-fuse-max-clear} \leq t_{derive-rec-delayed}$$

A match on both times indicates that the corresponding fuse coordinates with the recloser. In order to accommodate manufacturer tolerance and other error estimates, ±10% error curves are considered. A match within ±10% curves is then assumed valid as well.

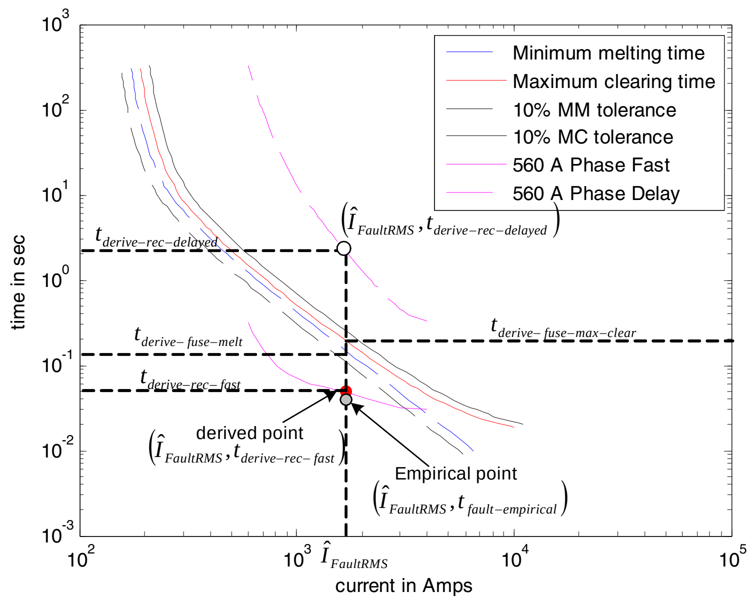

Figure 3-10
Recloser-Fuse Coordination: Fuse TCC Curves Must Be Between Recloser Fast and Delayed Curves (MM = Minimum Melt, MC = Maximum Clearing)

3.5 Identifying Fuse Operations

When a permanent or persistent temporary fault occurs, a fuse should blow to isolate the fault condition. The identifier algorithm recognizes a fuse operation by performing the following tasks:

- Compare the empirical point $\left(\hat{I}_{FaultRMS}, t_{fault-empirical}\right)$ to fuse TCC minimum melting and maximum clearing curves, and
- Compare the empirical I^2t of the event to the minimum I^2t of fuses used in the distribution feeder.

Table 3-5 and Figure 3-11 show functions and procedures carried out in identifying fuse operations. The analysis of the identification process is illustrated by way of an example in the next subsections.

Table 3-5
Functional Specification of Fuse Blowing Module

Sub-Modules	Functions	Outputs	Data Requirement
Fault Extracting Characteristics	Extracting Fault characteristics from voltage and current waveforms	Magnitude of Voltage sag, Fault current magnitude, and duration of fault	Voltage and Current waveforms. The time of voltage and current
TCC Comparison	Determining if extracted fault data matches a specified fuse characteristics	Fuse and Type	Magnitude of fault current, duration of fault, and TCC data for specified fuses
I^2t Comparison	Determining if I^2t extracted matches I^2t of specified fuses	Fuse and Type	Fuse and Type of TCC Comparison, TCC data for specified fuses

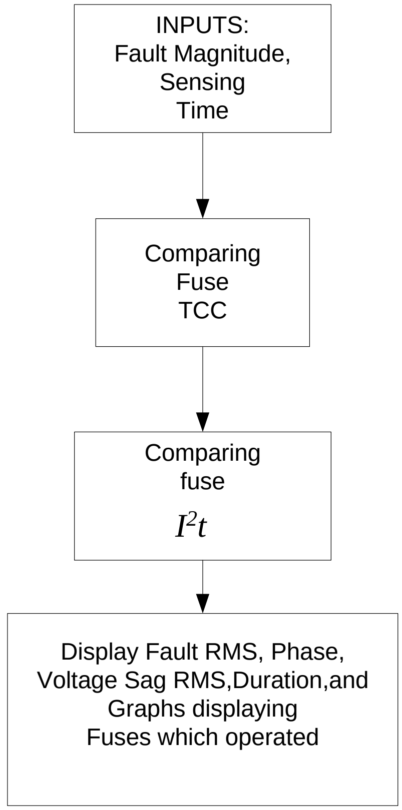

Figure 3-11
Procedure for Identifying Fuse Blowing Operations

3.5.1 Identifying Fuse Operations Using TCC Curves

Let the following event shown in Figure 3-12 be captured at the substation. The event was generated by PSCAD/EMTDC simulations by applying a permanent fault downstream from a 65 K fuse. The actual fault current seen by the fuse is 1.95 kA.

The fault magnitude and the corresponding duration are estimated using methods described in Section 3.2 and 3.3. The empirical fault coordinate is $\left(\hat{I}_{FaultRMS}, t_{fault-empirical}\right)$ = (1.6 kA, 0.0417 seconds). The fault point is then plotted and its distances (in terms of time duration) to fuse TCC curves are determined. The times corresponding to the fault magnitude $\hat{I}_{FaultRMS}$ on the minimum melt and maximum clearing curves can be estimated using an interpolation method. Let these times be $t_{derive\text{-}fuse\text{-}melt}$ and $t_{derive\text{-}fuse\text{-}max\text{-}clear}$, respectively. The estimated fault duration, $t_{fault\text{-}empirical}$ must be between two times, i.e.,

$$t_{derive-fuse-melt} \leq t_{fault-empirical} \leq t_{derive-fuse-\max-clear}$$

Any fuses in which their corresponding $t_{derive\text{-}fuse\text{-}melt}$ and $t_{derive\text{-}fuse\text{-}max\text{-}clear}$ satisfy the above requirement indicate an operation of the fuse. Since TCC curves of a 65 K fuse link meet this condition, it is identified as the fuse that operated to clear the fault. Other fuses that satisfy this condition are 50 K and 30T.

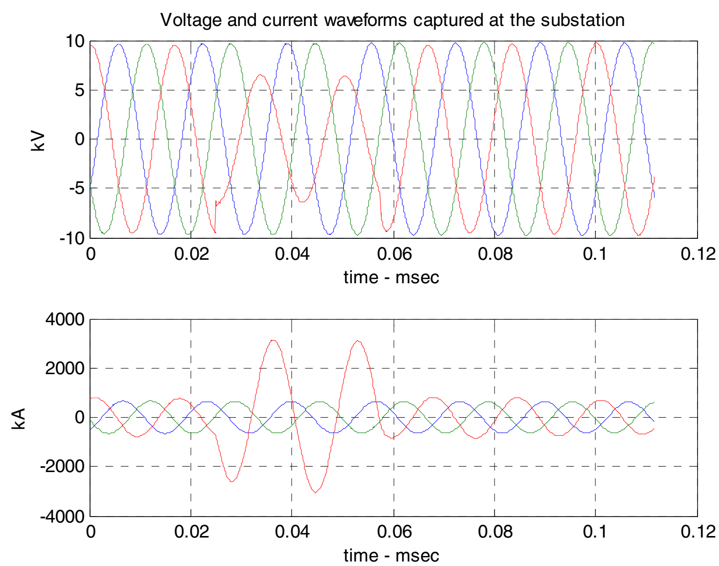

Figure 3-12
Voltage and Current Waveforms Seen at the Substation Due to the Operation of a 65 K Fuse

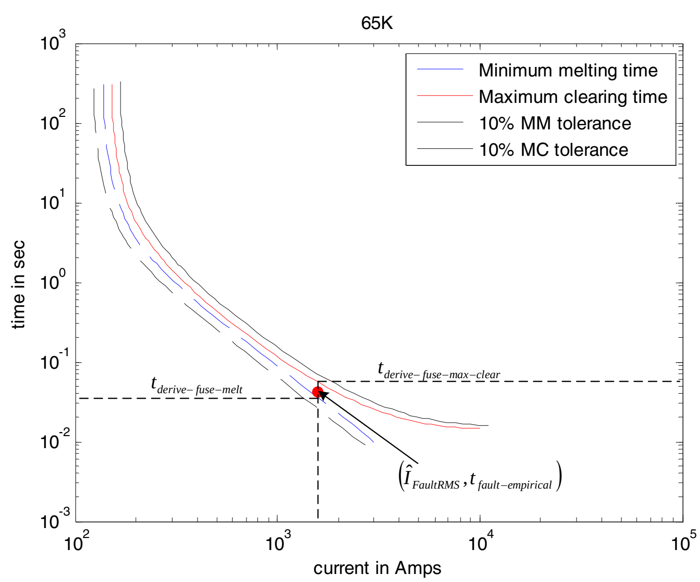

Figure 3-13
The Fault Point of a Fuse That Operates to Clear a Permanent Fault Is Situated in Between the Fuse TCC Minimum Melting and Maximum Clear Curves

3.5.2 Identifying Fuse Operations Using Fuse I^2t Characteristic

Since the minimum I^2t of a fuse indicates the minimum of amount of thermal energy for the fuse to melt, it can be effectively used to indicate a fuse operation. The comparison for I^2t is similar to TCC curve matching, in that the empirical I^2t value must be larger than the minimum melting I^2t value of the fuse protective device being used, i.e., $MinMelt_{I^2t} < Empirical_{I^2t}$. The minimum melt I^2t can be computed using data given in TCC tables. For the 65K fuse, the minimum melt I^2t is 90 kJ, while the empirical I^2t is 92.9 kJ. Therefore, the 65 K fuse link is identified as the fuse that operated in response to a fault. Other possible fuses are 50 K and 30 T links.

Fuses identified using these two comparison procedures (TCC and I^2t) can differ slightly. Therefore, only fuses identified in both procedures are considered as ones that operated. In this example, all identified fuses 50K, 65 K, and 30T appear in both comparison tests and one can assume that one of these fuses operates to clear the fault.

4
DEMONSTRATION AND EVALUATION OF THE IDENTIFIER ALGORITHM

The identifier algorithm described in Chapter 3 is implemented in Matlab for rapid prototyping and development. We will demonstrate that the identifier performs reasonably well for detecting recloser and fuse operations. Data for evaluating the identifier were generated using PSCAD/EMTDC simulation models as well as real data taken from a distribution substation.

4.1 Time-domain Simulation Models for Generating Fault Data

The time-domain simulation models were developed using PSCAD/EMTDC. We use the same circuit models described in Section 2.4. Circuits in Figures 2-6 and 2-11 are used for fuse blowing and saving scheme operations, respectively. The fault location is downstream from the protective devices. The fault magnitude can be varied by changing the fault impedance. There are two recloser relays, i.e., with phase and ground pickup currents of 560 A and 280 A, and a number of fuse types.

Voltage and current waveforms are captured at the secondary of the transformer, therefore, the measured current is the totalized current. Voltage and current waveforms have sampling rates of 256 samples/cycle and 128 samples/cycle, respectively. The length of the waveform is between 6 and 7 cycles.

4.2 Demonstration and Evaluation of the Identifier Algorithm in a Fuse Saving Scheme

As described earlier in Section 3.4, a complete fault clearing operation in a fuse saving scheme can take up to one second or more. Therefore, the entire fault clearing operation is partitioned and recorded as several independent events by a power quality monitor. The identifier algorithm as reported herein only identifies the first and second recorded events only, and determines all possible fuses that coordinate with the recloser.

4.2.1 Case 1 – Recloser Operation – a Phase Pickup Relay Detects the Fault

A single-line to ground fault is applied downstream from the 65T fuse and requires at least two fast operations to clear. The fault current seen by the recloser is about 2.1 kA. Based on the fast TCC curve, the phase pickup recloser is set to interrupt in 0.04 seconds, or 2.4 cycles.

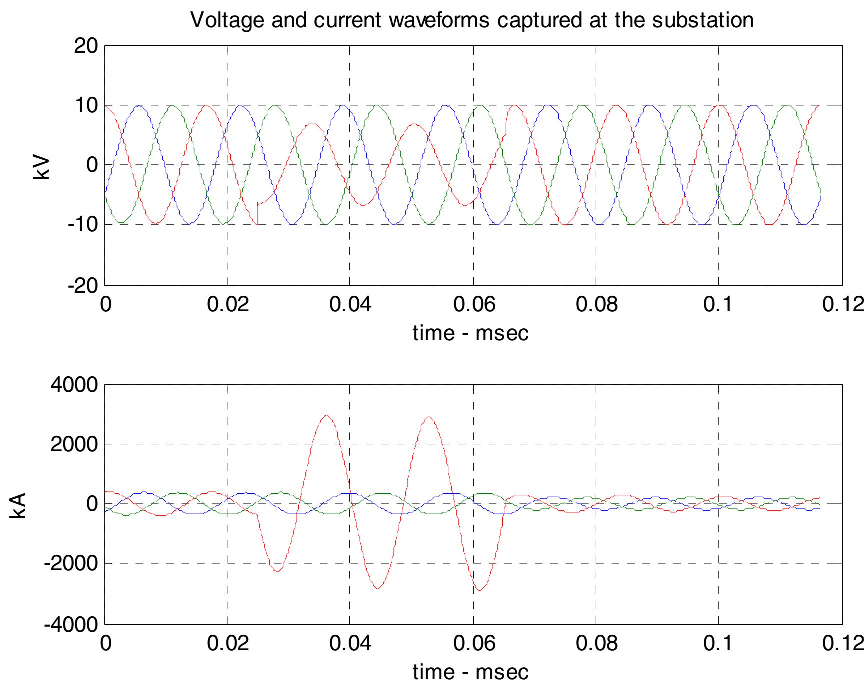

Figure 4-1
The First Fast Recloser Operation Captured at the Substation (560 A Overcurrent Phase Relay)

Voltage and current waveforms of the recloser first fast operation are shown in Figure 4-1. The identifier algorithm analyzes these waveforms. It correctly identifies that the recloser with a phase pickup relay (560 A) indeed operates. The fault magnitude and duration estimates are 1.7 kA and 0.05 seconds. These estimates are reasonably accurate.

The identifier then determines fuses that can coordinate with this recloser. Based on the analysis, there are four fuses, i.e., 65T, 85T, 100T, and 140T. The actual fuse used in the simulation is 65T; therefore, the identifier performs its functions correctly.

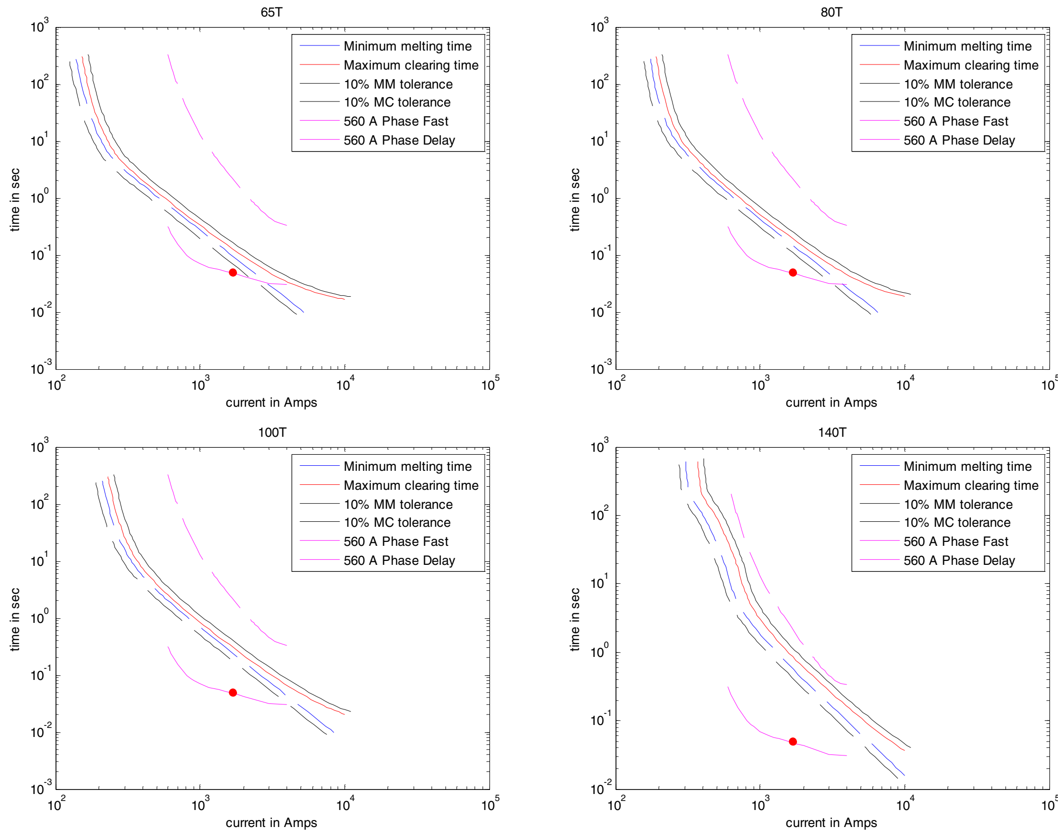

Figure 4-2
The identifier indicates that the voltage and current waveforms shown in Figure 4-1 is caused by an SLG fault on Phase C. The recloser that operated to clear the fault is a recloser with phase pickup current of 560A. Fuses that coordinate with this recloser are 65T, 80T, 100T, and 140T.

Since the fault persists, the recloser performs a second fast operation. The corresponding waveforms are shown in Figure 4-3. The identifier algorithm outputs indicate that the event is due to an SLG fault on phase C, and a recloser (560 A overcurrent phase relay) operates. Fuses that coordinate with the recloser are the same as those in the first fast operation. Therefore, the identifier performs its function correctly.

Note that the identifier algorithm is not designed to correlate multiple events. Therefore, the identifier does not know which of the two events the first or second fast operation is. The delayed recloser operation is not analyzed since the event is truncated (most PQ monitors only capture about seven cycles of the waveform). Thus the algorithm cannot estimate the duration of the fault seen by the recloser. Future work will include these analyses.

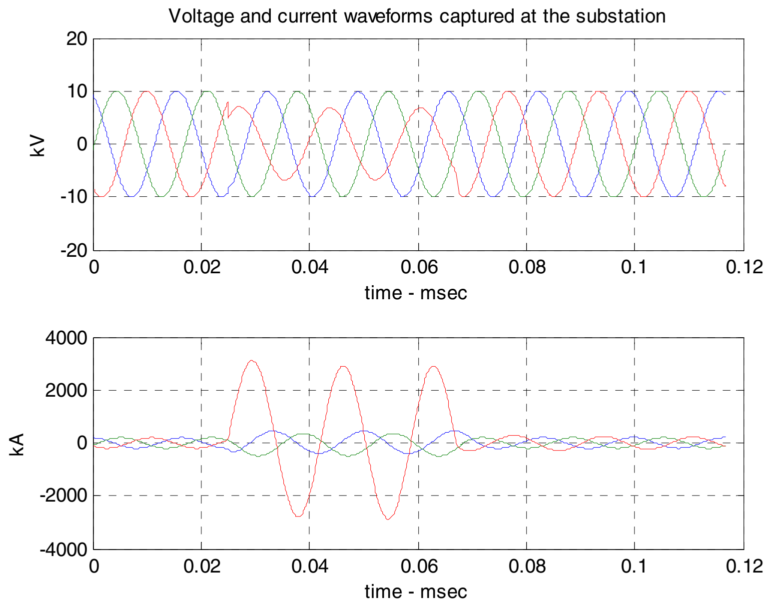

Figure 4-3
The Second Fast Recloser Operation Captured at the Substation

4.2.2 Case 2 – Recloser Operation – Ground Pickup Relay Detects the Fault

This case is similar to that in Case 1; however, it is the recloser overcurrent ground relay that detects the fault. The actual current magnitude at the recloser is 1.26 kA. From the TCC curve, the recloser should open in 0.04 seconds. Voltage and current waveforms from the first fast operation captured at the substation is shown Figure 4-4.

The identifier algorithm estimates that the fault current seen by the recloser is 1.1 kA with duration of 0.05 seconds. The identifier correctly estimates that the recloser (280A overcurrent ground relay) operates. Furthermore, it also gives an accurate estimate of fuses that coordinate with the recloser, i.e., 40T, 50T, 65T, 80T, and 100T.

Voltage and current waveforms of the second fast operation are shown in Figure 4.6. For this operation, the identifier also correctly determines the recloser operation and fuses that coordinate with the recloser. There are slight differences though; it identifies the following reclosers, 50T, 65T, 80T, 100T, and 140T. From these results, it is apparent that the identifier correctly determines the recloser type and fuses that coordinate with the recloser.

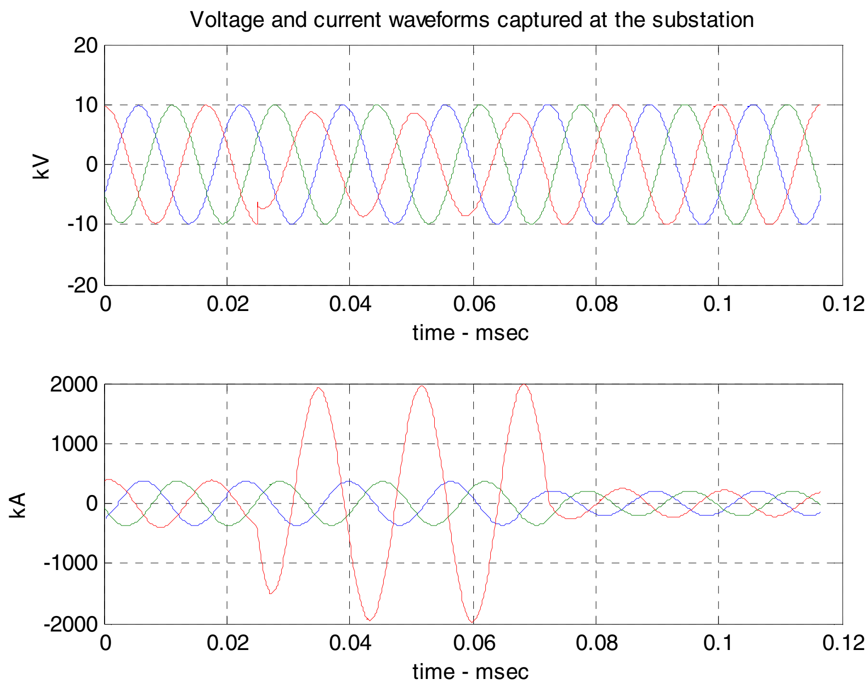

Figure 4-4
The First Fast Recloser Operation Captured at the Substation (Overcurrent Ground Relay)

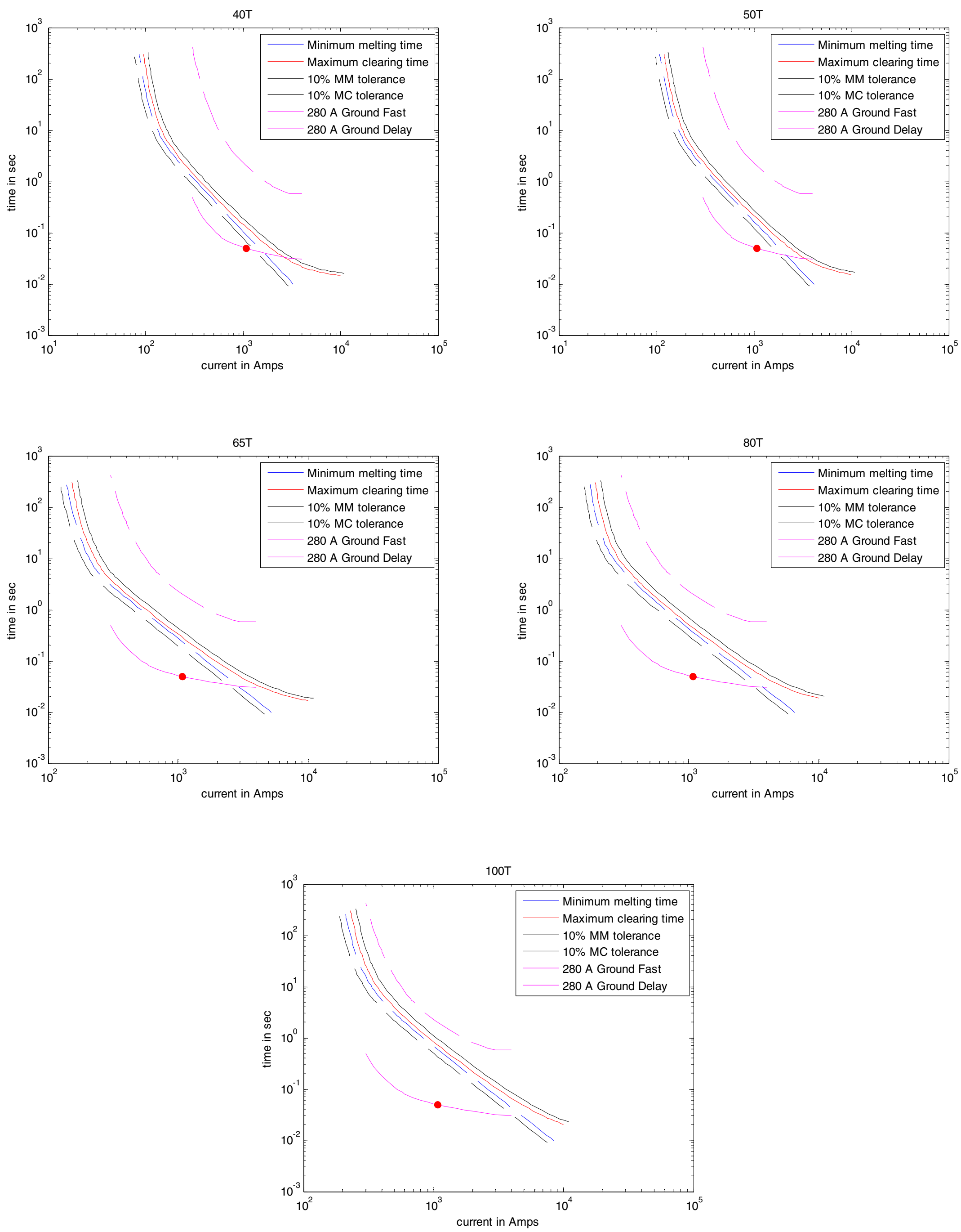

Figure 4-5
The identifier indicates that the voltage and current waveforms shown in Figure 4-4 is caused by an SLG fault on Phase C. The recloser that operates to clear the fault is a recloser with phase pickup current of 280A. Fuses that coordinate with this recloser are 40T, 50T, 65T, 80T, and 100T.

Note that in analyzing the above two case, the identifier was given an indicator that the utility employs a fuse saving scheme. If an incorrect indicator is given, the identifier algorithm predicts that fuses [65K, 30T, 40T] and [40K and 25 T] operate in Case 1 and 2, respectively. The identifier performs its analysis correctly since the empirical fault points match nicely with the corresponding TCC fuses. However, the results are not in agreement with the actual fuse used in the simulation model since an incorrect indicator was given.

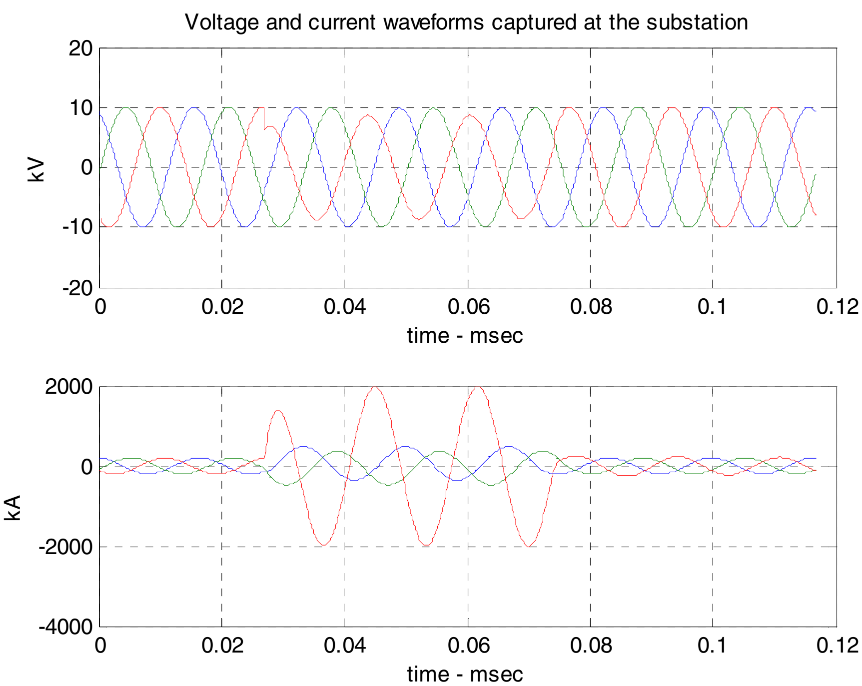

Figure 4-6
The Second Fast Recloser Operation Captured at the Substation (Overcurrent Ground Relay)

4.3 Demonstration and Evaluation for Identifying Protective Device Operation in a Fuse Blowing Scheme

This section presents two permanent fault clearing cases. The identifier algorithm is given an indicator that the utility employs a fuse blowing practice.

4.3.1 Case 3 – Fuse Operation – 65 K

The fuse used in the simulation model is a 65 K fuse. The fault current seen by the fuse is 1.9 kA (based on the simulation). Voltage and current waveforms captured at the substation are shown in Figure 4-7.

The identifier estimates that the fault current is 1.6 kA with duration of 0.042 seconds. It determines that the fuse that operates to clear the fault is one of the following fuses 50K, 65K, and 30T. Figure 4-8 shows the fuse TCC curves. This result is correct since the fuse used in the simulation is a 65K fuse.

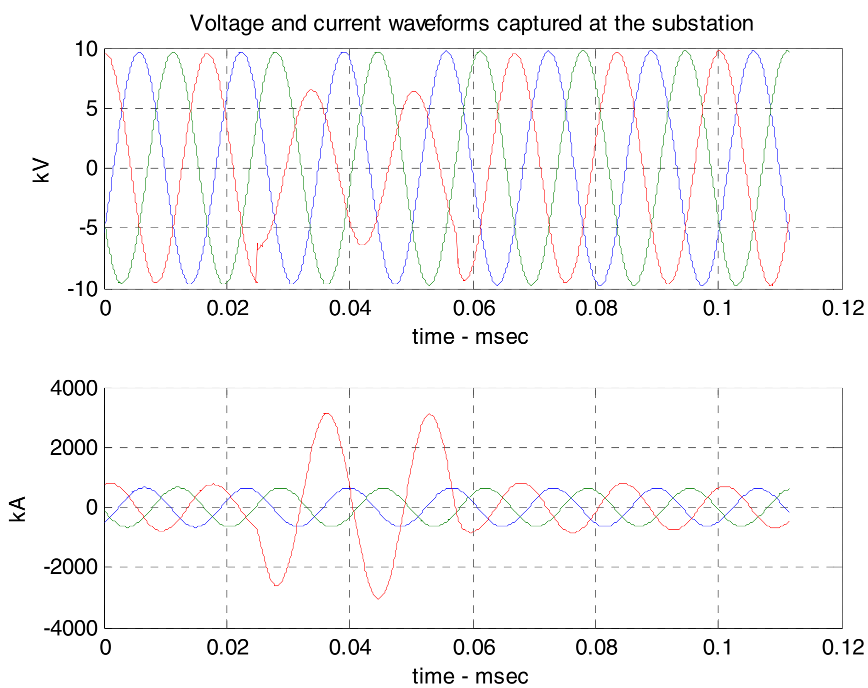

Figure 4-7
Voltage and Current Waveforms Capture at the Substation. The Fuse Used in the Simulation Model is 65K

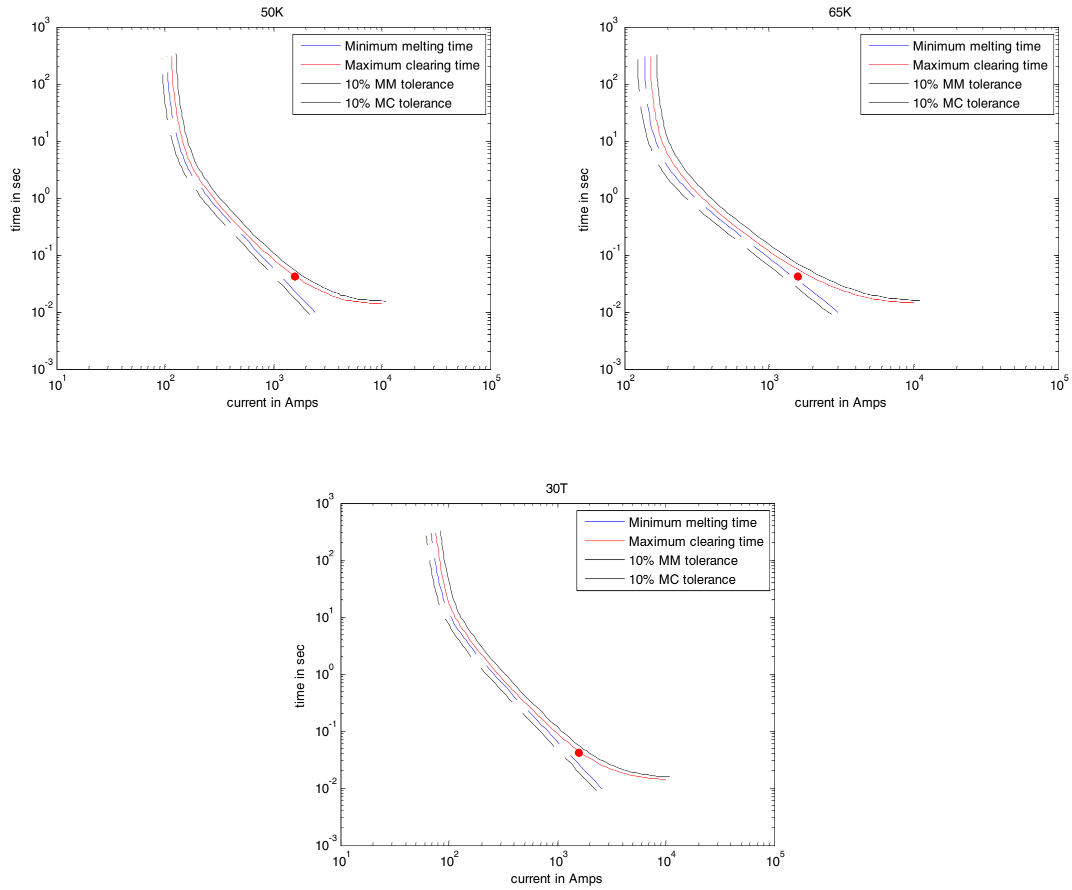

Figure 4-8
The Identifier Determines That One of These Fuses Interrupt the Fault Event Shown in Figure 4-7

4.3.2 Case 4 – Fuse Operation – 65 K, Low Fault Current

Case 4 is similar to that in Case 3, however, the fault current seen at the fuse is 1.30 kA (obtained using simulation). Voltage and current waveforms are shown in Figure 4-9. The estimated fault current and duration seen by the fuse are 1.17 kA and 0.067 seconds. The identifier determines that one of the following fuses operates to clear the fault, i.e., 50K, 65K, and 30T (see Figure 4-10). This analysis is correct since the actual fuse used in the simulation is 65 K.

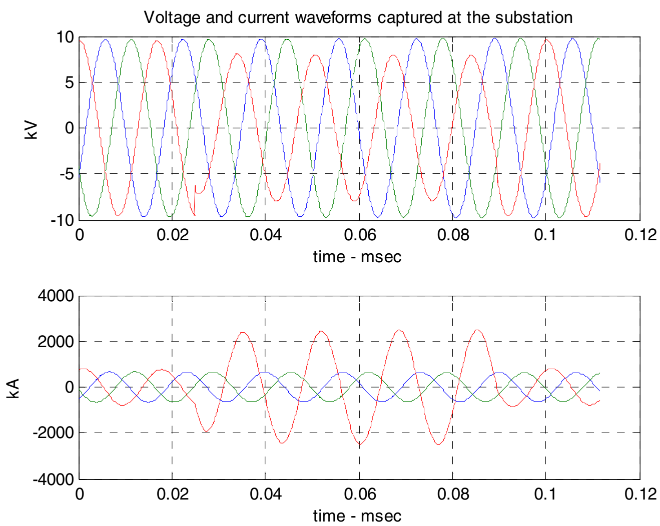

Figure 4-9
Voltage and Current Waveforms Capture at the Substation. The Fuse Used in the Simulation Model Is 65K. The Fault Current Is Lower Than That in Figure 4-7.

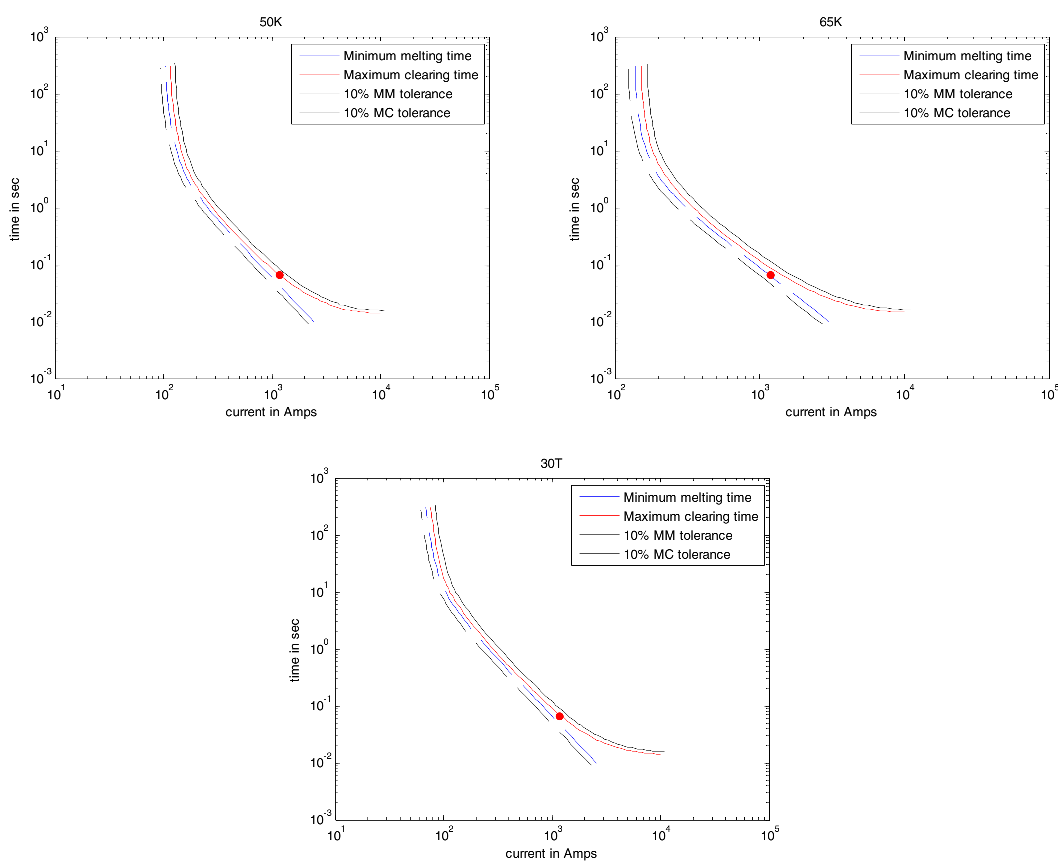

Figure 4-10
The Identifier Determines That One of These Fuses Interrupt the Fault Event Captured in Figure 4-9

4.4 Demonstration and Evaluation for Identifying Protective Device Operation in a Fuse Blowing Scheme: Real Data

This Section demonstrates the application of the identifier algorithm in analyzing real data collected at an actual distribution substation. In all cases below, it is assumes that the utility employs a fuse blowing scheme.

4.4.1 Case 5 – Actual Fuse Operation - Event A

Voltage and current waveforms captured at the substation are shown in Figure 4-11. The identifier estimates that the fault current seen by the fuse is 2.3 kA with duration of 0.025 seconds. The identifier determines that one of the following fuses interrupt the fault, 40K, 50K, 65K, 25T, 30T, and 40T, as shown in Figure 4-12. The GIS maps for the circuit indicated that the fuse size that was at this location was a 65K, which was one of the fuses identified by the algorithm (the utility only uses K links, so we can ignore the T links in the algorithm results).

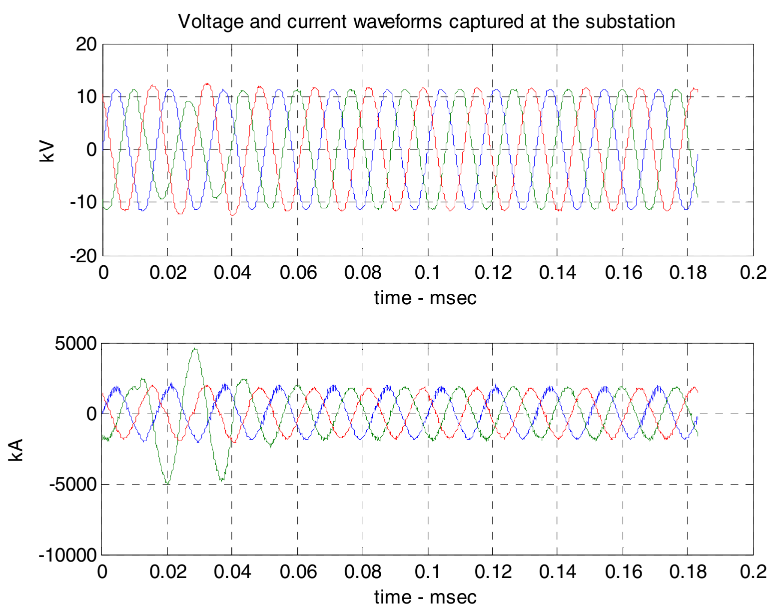

Figure 4-11
Real Voltage and Current Waveforms Capture at the Substation: Event A

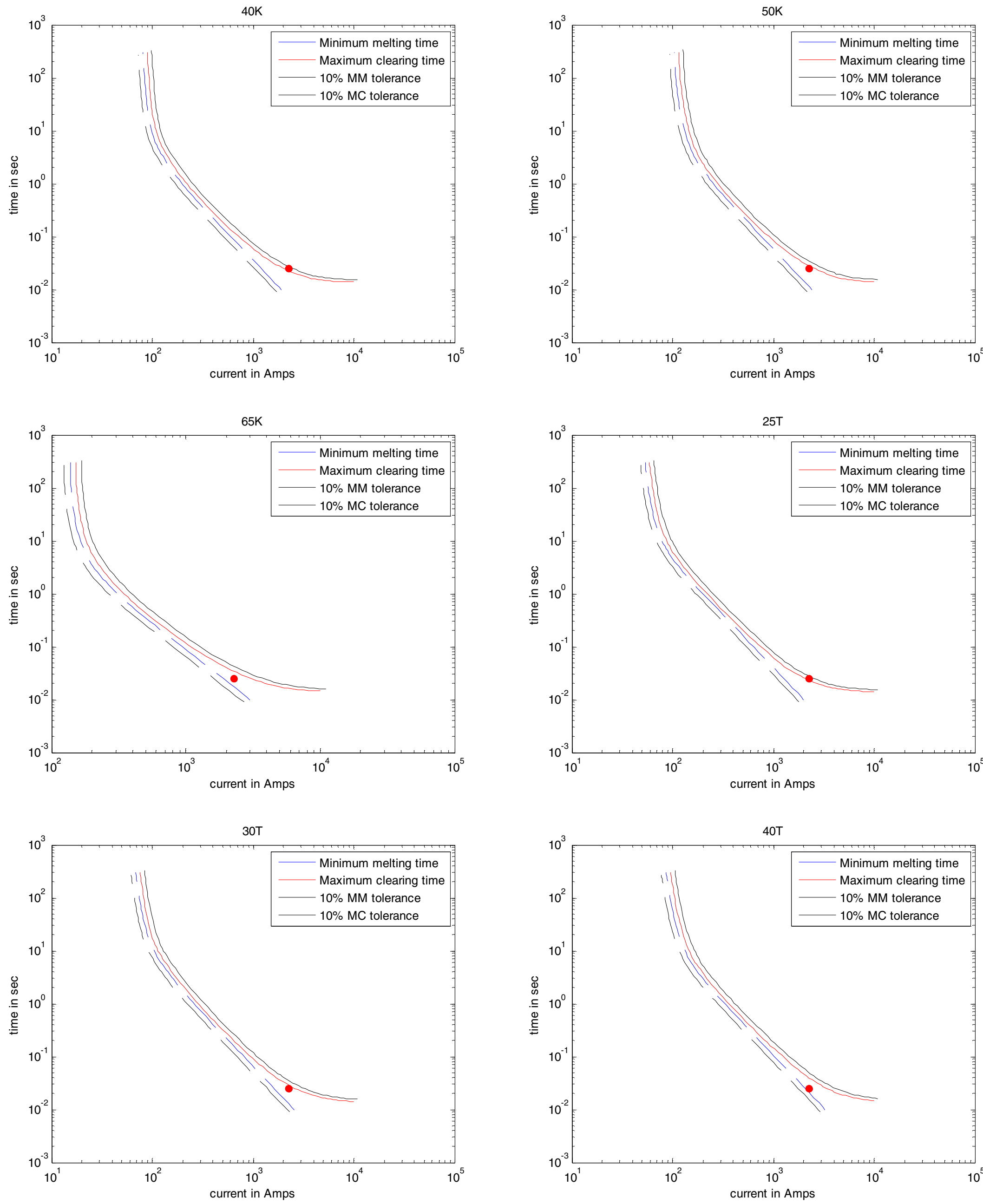

Figure 4-12
The Identifier Determines That One of These Fuses Interrupted the Event A Fault Current

4.4.2 Case 6 – Actual Fuse Operation - Event B

Voltage and current waveforms for Event B captured at the substation are shown in Figure 4-13. The estimated fault current seen by the fuse is 2.43 kA with duration of 0.033 seconds. The identifier determines that one of the following fuses interrupted the fault, 65K, 80K, 40T, and 50T, as shown in Figure 4-14. The GIS maps for the circuit indicated that the fuse size that was at this location was a 65K, which was one of the fuses identified by the algorithm.

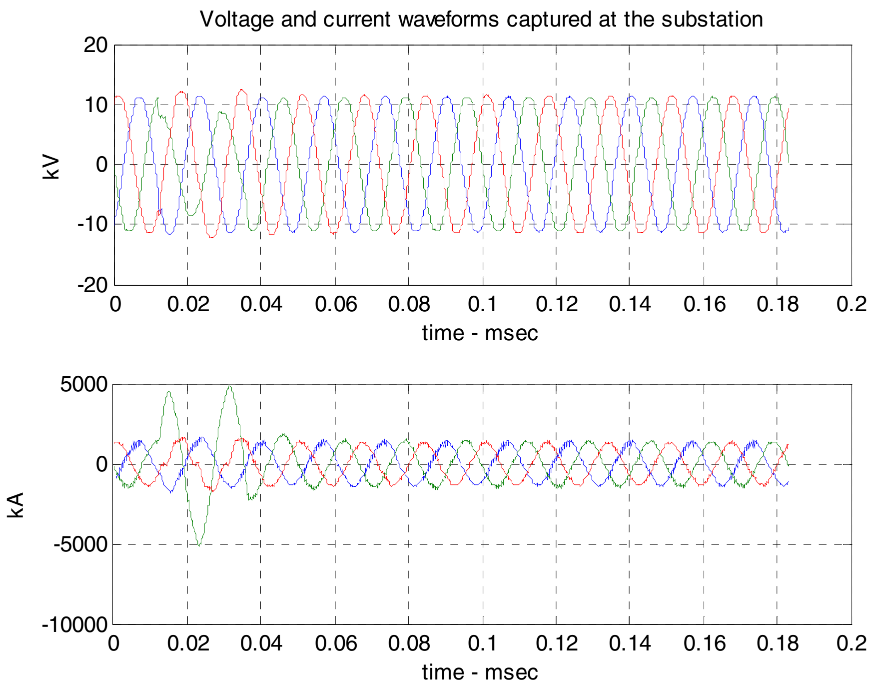

Figure 4-13
Real Voltage and Current Waveforms Capture at the Substation: Event B

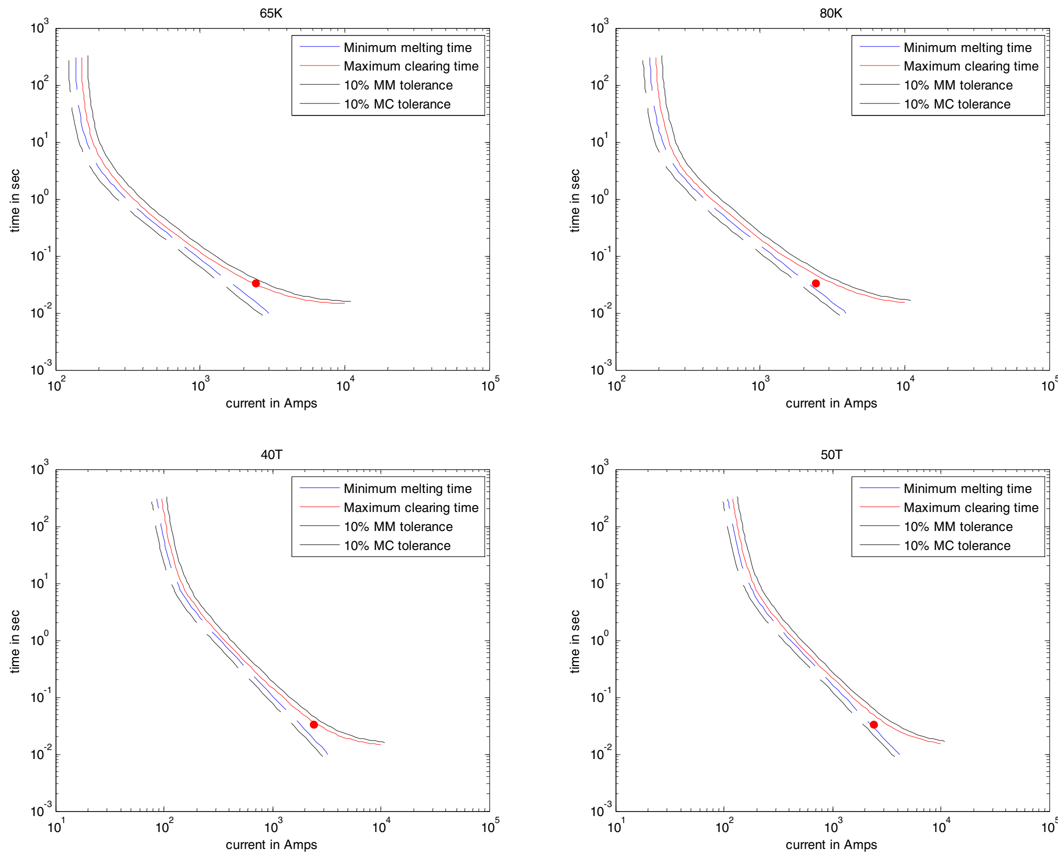

Figure 4-14
The Identifier Determines That One of These Fuses Interrupted the Event B Fault Current

4.4.3 Case 7 – Actual Fuse Operation - Event C

Voltage and current waveforms for Event C captured at the substation are shown in Figure 4-15. The estimated fault current and duration are 1.35 kA and 0.025 seconds, respectively. The identifier determines that one of the following fuses interrupted the fault, 25K, 30K, 40K, 15T, 20T, and 25T as shown in Figure 4-16. The GIS maps for the circuit indicated that the fuse size that was at this location was a 50K, which was not one of the fuses identified by the algorithm. Several explanations could explain the discrepancy:

- The algorithm didn't work correctly (this is a low-magnitude fault relative to the load current, which makes it difficult for the algorithm).
- The times were off by more than four hours between the outage report and the monitoring data, so the events may not be the same.
- The fuse location may have been misidentified.
- The wrong fuse may have been installed (this is the type of problem this algorithm is meant to identify).

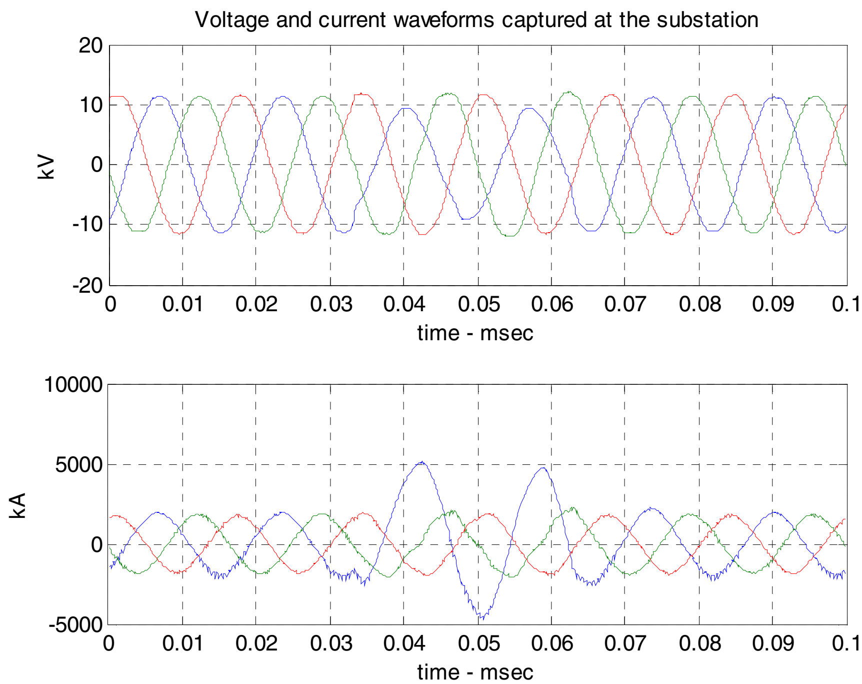

Figure 4-15
Real Voltage and Current Waveforms Capture at the Substation: Event C

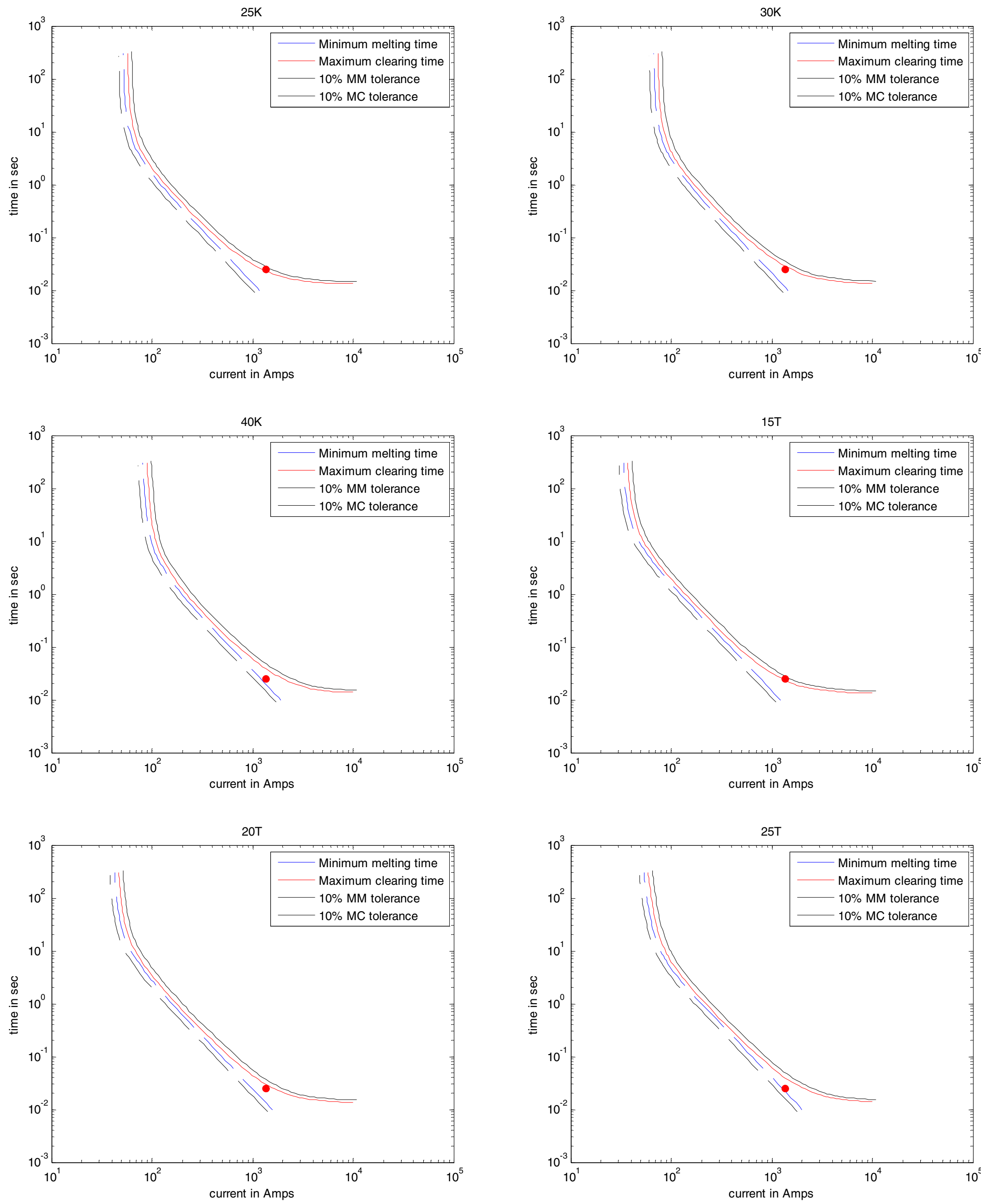

Figure 4-16
The Identifier Determines That One of These Fuses Interrupted the Event C Fault Current

4.4.4 Case 8 – Actual Device Operation - Event D

Voltage and current waveforms for Event D captured at the substation are shown in Figure 4-17. The estimated fault current seen by the protective device is 1.27 kA with duration of 0.0583 seconds, respectively. The identifier determines that one of the following fuses interrupt the fault, 40K, 50K, 65K, 25T, and 30T as shown in Figure 4-18. The actual device that interrupted the fault current is unknown.

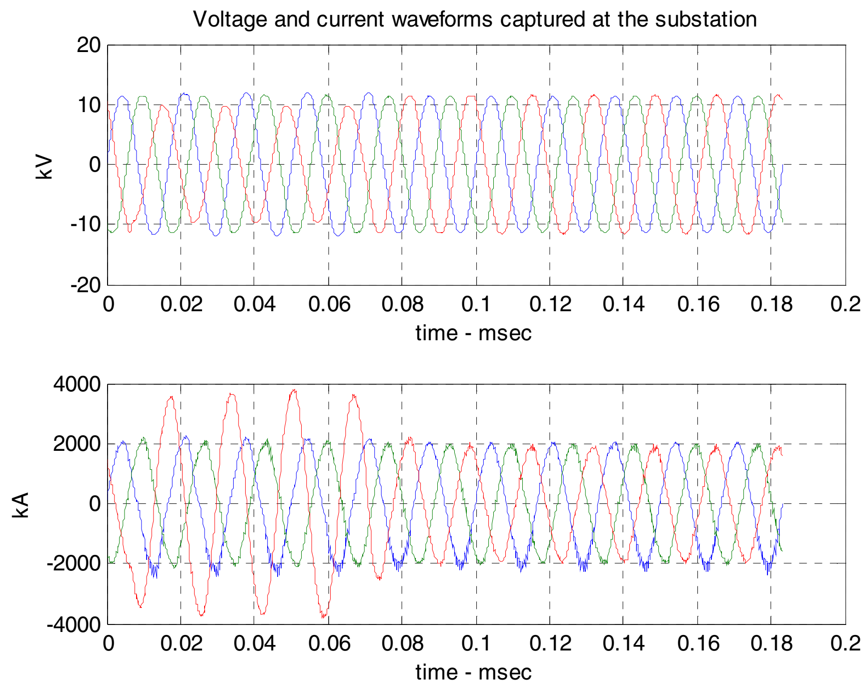

Figure 4-17
Real Voltage and Current Waveforms Capture at the Substation: Event D

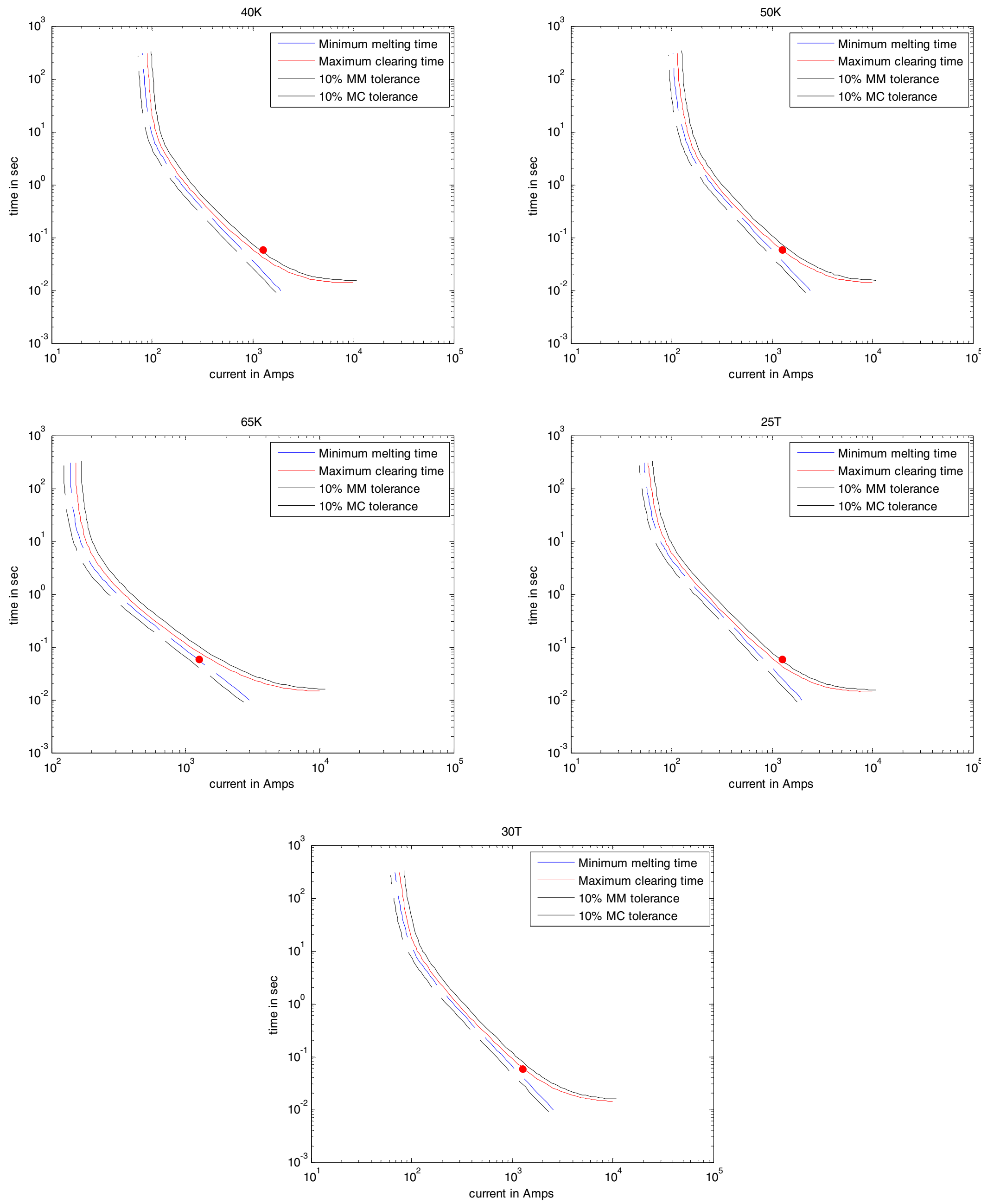

Figure 4-18
The Identifier Determines That One of These Fuses Interrupted the Event D Fault Current

The above cases demonstrate that the initial development of identifier performs reasonably well. There are of course many aspects of the identifier that should be improved. This will be addressed in the next chapter.

5
FUTURE WORK

Overcurrent protection in distribution systems involves the coordination between different levels of protective devices. Time settings of these devices are determined in protection coordination studies and subsequently programmed into overcurrent relays. Unfortunately, there are instances where poor or mis-coordination occurs. Certainly, under such circumstances, power quality and reliability will be adversely impacted.

This report presents a proof of concept algorithm to identify the operation of overcurrent protective devices, especially fuses and line reclosers. The algorithm represents an initial step in developing a fully automatic analysis system to evaluate distribution system overcurrent protection coordination. The identifier algorithm, at minimum, requires three-phase voltage and current waveforms captured upstream from overcurrent devices being monitored. In addition, the algorithm needs to know the utility fault clearing scheme, i.e., whether it is based on the fuse saving or fuse blowing scheme. Data on types of overcurrent protective devices used in the distribution feeders and their corresponding TCC curves are desirable. However, when they are not provided, the algorithm assumes that the distribution feeders use all types of K and T fuses.

The algorithm works by estimating the fault current magnitude seen by the protective device and the duration during which the fault current flows in the device. The algorithm then determines which protective device time-current characteristic curves match these two parameters the closest. Ones that do are considered as the protective devices that operate to interrupt the fault current. This is essentially how the algorithm identifies fuse operations. In this initial work, we consider K and T link fuses only.

Identifying recloser operations is more complex since there are several shots in the fault clearing sequence. For this work, a four-shot sequence is assumed, i.e., two fast and two delayed operations. The entire clearing sequence may take one or more seconds. Since most power quality monitors do not record disturbance waveform for duration of one second, the sequence is partitioned into several disturbance events. In this work, the algorithm assumes that all events are independent and only the first two fast operations are analyzed. Ideally, these individual events must be correlated so as to determine whether the fault is permanent or temporary. In addition, delayed events should be analyzed as well. This will allow the identifier to evaluate the proper recloser-fuse coordination. However, since the correlation algorithm is not developed, the identifier algorithm does not know which event is the first or second fast operation, or first or second delayed operation since they are independent events.

Since the correlation algorithm is not available, upon identifying the recloser that operated, the algorithm then proceeds to determine fuses that coordinate well with the recloser.

Future work to enhance the algorithm is as follows:

- Improve the recloser model and fault clearing sequence so that more data can be generated more easily. In this work, recloser timings are entered manually to the simulation model. Ideally the simulation model can read off recloser times directly from TCC curves.
- Improve the estimation of the fault current magnitude and duration seen by the protective device. These two parameters are critical in determining the operation of the overcurrent protective device.
- Improve the interpolation method to obtain the derived time based on the estimated fault current magnitudes. The interpolation is rather complicated since TCC curves possess a logarithmic behavior.
- Develop an algorithm to correlate events that occur within a few seconds. These events can be due to recloser operations. Once the correlation algorithm is developed, it allows the identifier algorithm to better identify the recloser-fuse coordination.

Since many PQ monitors limit a waveform event to seven cycles or so, it is necessary to include RMS data source in analyzing recloser delayed operations. This analysis should be incorporated in the future development.

6
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A
RPAD WEB-BASED USER INTERFACE

Appendix A covers the graphical user interface that was created using Rpad. The goal of the user interface is to identify which overcurrent protective devices that would operate during fault conditions. This identification allows the user to determine if the devices on their system are coordinated. Figure A-1 below shows the Rpad graphical user interface. The codes in Rpad are developed based on those used in Matlab. However, some functions are not readily available in Rpad and had to be simplified. Because some of the Rpad functions are simpler they can be less accurate. For example MATLAB uses polynomial approximation for an interpolation technique while Rpad uses linear interpolation.

The Rpad graphical user interface allows the user to modify a radial distribution system by selecting the overcurrent protection devices and scheme. The user can then check the protective device coordination by testing different fault conditions. The fault conditions are entered as comma delimited data points of voltage and current waveforms seen by a power quality monitor. The power quality monitor is located upstream from the protective devices and can observe seven cycles of data at a time. The Rpad code detects and extracts the fault magnitude and duration from the voltage and current data and plots the waveforms. The extracted fault data are compared to the TCC curves of the protective devices selected by the user. If the fault magnitude and time fall between a fuse's melting curves, the fuse is identified as operating and its TCC curve is plotted. If the fuse saving scheme is used and the fault magnitude and time fall above the fast operation curve of a recloser, the recloser TCC curves and fuses TCC curves that coordinate with the recloser are plotted.

An example is used to illustrate how to enter data into the Rpad GUI and how the Rpad code identifies protective device operation. Data for evaluating the Rpad code comes from a time-domain simulation model developed using PSCAD/EMTDC. A permanent fault, fuse blowing model similar to Case 3 described in Section 4.3 is modeled in PSCAD. The simulation generates fault data that is converted into a comma delimited CSV text file using Matlab code.

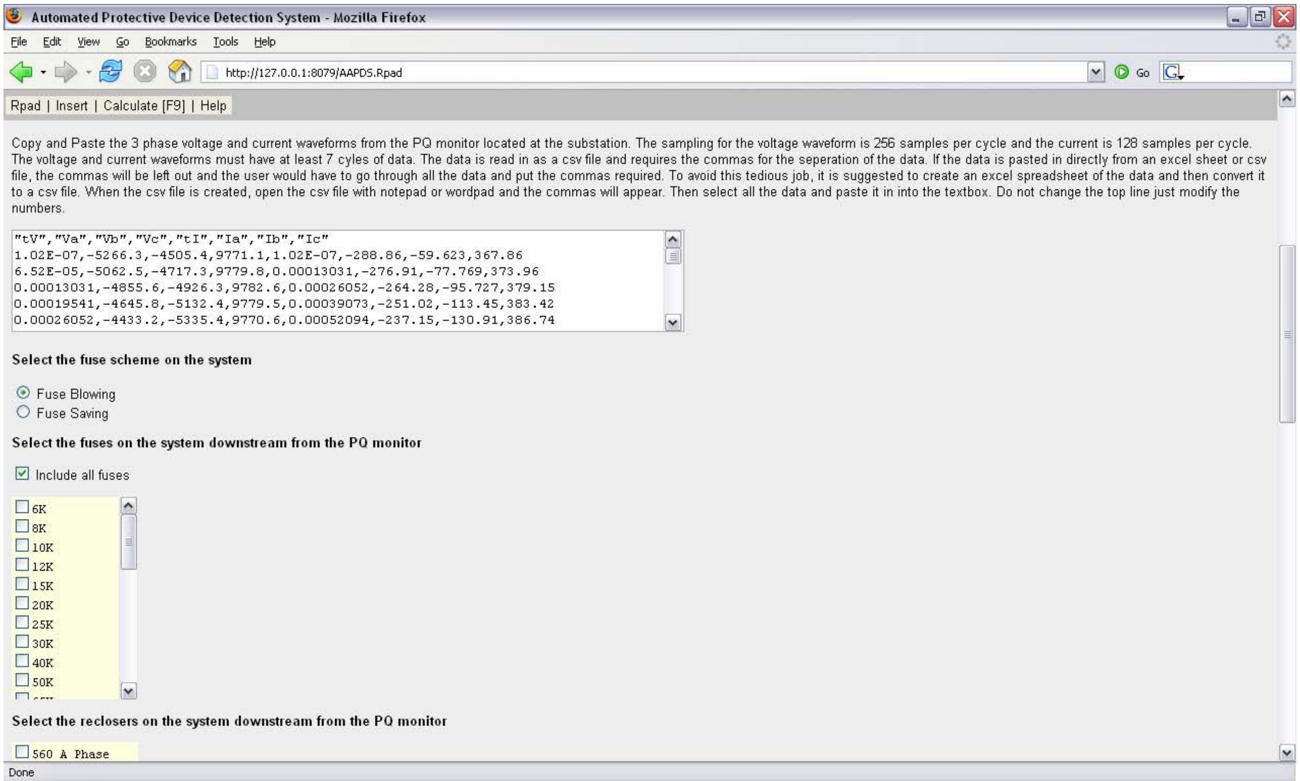

Figure A-1
Implementation of the Identifier in Rpad

A.1 Graphical User Interface

As mentioned above, the graphical user interface allows the user to modify the overcurrent protection devices and scheme. Protection device coordination is checked by testing device operation during different fault conditions viewed by a power quality monitor. The power quality monitor records three phase voltage and current waveforms for six to seven cycles.

A.1.1 Entering Power Quality Monitor Waveforms Into the Rpad GUI

Usually waveform data points are saved as a data table into a CSV text file. For example, the PSCAD/EMTDC simulations record the time stamped data points into a text file which is converted into a comma delimited CSV data table using Matlab code. The CSV file is opened with an application like Notepad so that the commas separating the columns of the data table are shown. The waveform data table is then copied and pasted into the GUI text box shown below in Figure A-2.

```
"tV","Va","Vb","Vc","tI","Ia","Ib","Ic"
3.84E-07,-5236.2,-4826.6,10064,3.84E-07,-155.3,-33.255,187.24
6.55E-05,-5023.7,-5041.9,10067,0.00013059,-148.79,-43.027,190.45
0.00013059,-4807.9,-5254.4,10064,0.0002608,-141.93,-52.694,193.2
0.0001957,-4589.6,-5463.4,10054,0.00039101,-134.72,-62.232,195.49
0.0002608,-4368.4,-5669.1,10039,0.00052122,-127.18,-71.62,197.3
```

Figure A-2
Data Format in Rpad

The data labels are given in the Rpad GUI text box. The Rpad code requires a timestamp for the voltage waveforms, the three phase voltage waveforms, a timestamp for the current waveform, and the three phase current waveforms. Two separate timestamps are required for the voltage and current waveforms since their sampling rates are different. The voltage waveform is sampled at approximately 256 samples/cycle while the current waveform is sampled at approximately 128 samples/cycle. The Rpad code saves the data table in the text box as a CSV file and stores the data in a variable as a data frame using the ‘read.csv’ function.

A.1.2 Overcurrent Protection Device and Scheme Selection

The next step is for the user to select the fuse scheme for the system. For a fuse blowing scheme, the only overcurrent protective devices on the system are fuses. For a fuse saving scheme, a recloser operates first if the protective devices on the system are coordinated. Since the waveform is only six to seven cycles long, it is impossible to tell if the fault is temporary or if a fuse will operate to clear the fault. The Rpad code identifies the recloser based on its fast operation TCC curve and identifies the fuses that coordinate with the recloser.

The next step is to modify the system by selecting the fuses from the list. If the types of fuses are unknown or if the user wants to find out which fuses would operate for specified fault conditions, the user can select the “Include all fuses” option. If the fuse saving scheme is used, the user selects which recloser curves to use. An error message appears if a recloser is not selected. When the data is updated, the user clicks the ‘Calculate’ button to view the results.

For the fuse blowing permanent fault PSCAD/EDMTC simulation model, the ‘Fuse Blowing’ option is selected. The ‘Include all fuses’ check box is selected to test if the Rpad identifier algorithm can accurately detect the 65K fuse on the system. After running the Rpad code, the identifier algorithm accurately detects that a 65K fuse cleared the system. The algorithm also indicates that a 30T fuse and a 50K fuse could have cleared the fault too. The fault magnitude and duration estimates are 1.17 kA and 0.0667 seconds.

A.2 Extracting Fault Characteristics

To extract fault characteristics the Rpad algorithm first finds the nominal system voltage and load current and determines if fault conditions exist by detecting changes in the waveform. In order to determine the nominal voltage and load current, the waveform is broken down into cycles and each cycle is examined. The positive and negative peak values of the voltage are stored into an array. The nominal voltage on the system is calculated by taking the median of the peak values in the array. If the fault duration is longer than duration of the waveform, the nominal system voltage and current are set to the first peak values of the waveform. Each peak of the waveform is compared to the nominal voltage or to the load current to test for fault conditions. Fault conditions exist if the voltage sags below 95% of the nominal system voltage and if the current exceeds 150% of the load current.

The fault duration is calculated by summing the number of negative peaks and positive peaks that satisfy fault conditions. Each phase of the waveform is checked for fault conditions and if fault conditions exist the phase waveforms are plotted. If no fault was detected, an error message lets the user know that there was no fault on the system.

The current that exceeds 150% of the load current is the sum of the load current plus the fault current. The Rpad algorithm has two methods for calculating the fault current. The first method calculates the fault current by taking the difference between the total current and the load current. The second method estimates the fault impedance by taking the difference between the load impedance and the total impedance. The fault current magnitude is calculated by dividing the fault impedance by the voltage sag values. The fault magnitude is the average of these two values.

A.2.1 TCC Comparison

The calculated fault magnitude and duration are compared to the TCC curves of the user selected fuses. The Rpad algorithm compares the calculated fault magnitude to the RMS current magnitude values from the maximum clearing curve. The times on the maximum clearing curve corresponding to the fault current are read from the TCC curves. If the time from the curve is greater than the derived fault duration time, then the fuse did not operate. Next, the fault magnitude is compared to the minimum melting curve. The time from the minimum melting curve that corresponds to the fault magnitude is compared to the derived fault duration. If the minimum melting time is less than the fault duration, then the fuse did not operate. Each of the fuses selected by the user is compared to the fault magnitude and duration and kept in an array if they satisfy the above conditions.

Next the fuses that match the TCC criteria above are compared to the calculated thermal energy of the fault current and magnitude. The thermal energy is equal to the square of the fault current magnitude multiplied by the fault duration. If the derived thermal energy is below the thermal energy of the maximum clearing curve and greater than the thermal energy of the minimum melting curve, the fuse will melt.

A.2.2 Fuse Scheme

During a fault, a recloser operates first for a system utilizing a fuse saving scheme. The voltage and current waveforms seen by the power quality monitor display the fault magnitude but the duration of the fault is actually the first fast curve operation time of the recloser. Since it is impossible to determine if the fault was cleared by the recloser or by fuses during a recloser delayed operation, the Rpad algorithm determines what recloser operated and the fuses that coordinate with the recloser. The derived fault magnitude is compared to the points of the fast recloser operation curve. The time corresponding to the fault current is extracted from the curve and compared to the calculated fault duration.

A.3 Output

Finally the results of the analysis are plotted. The following example is similar to Case 1 in Section 4.2. The waveform data is taken from the fuse saving PSCAD/EDMTC simulation with a downstream 65T fuse. A single line to ground fault is applied downstream from the 65T fuse. The fault seen by the recloser is about 2.1 kA. Based on the TCC curve, the phase pickup recloser is set to interrupt in 0.04 seconds. The fuse saving scheme is selected and all fuses are tested for the Rpad GUI.

Voltage and current waveforms of the recloser first fast operation are shown in Figure A-3. The identifier algorithm correctly identifies that the phase pickup relay operates. The fault magnitude and duration estimates are 1.7 kA and 0.05 seconds. The identifier determines fuses that might coordinate with the recloser. Based on the analysis, there are 6 fuses; 100K, 140K, 65T, 80T, 100T, and 140T. The fuse and phase recloser TCC plots are shown below in Figure A-4. Because the Rpad codes are in their initial stage, the results may vary slightly from the Matlab analysis results. The actual fuse used in the simulation is a 65T fuse; therefore the identifier performs its function correctly.

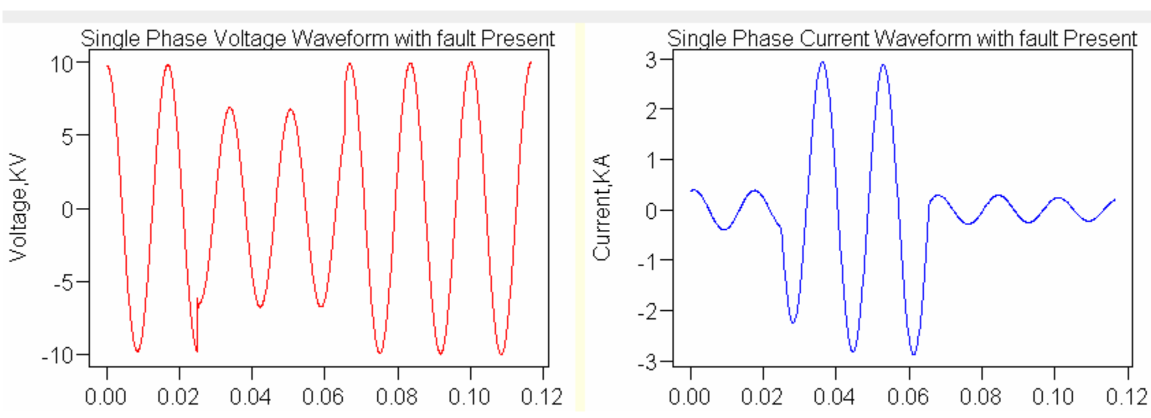

Figure A-3
Voltage and Current Waveforms on Rpad

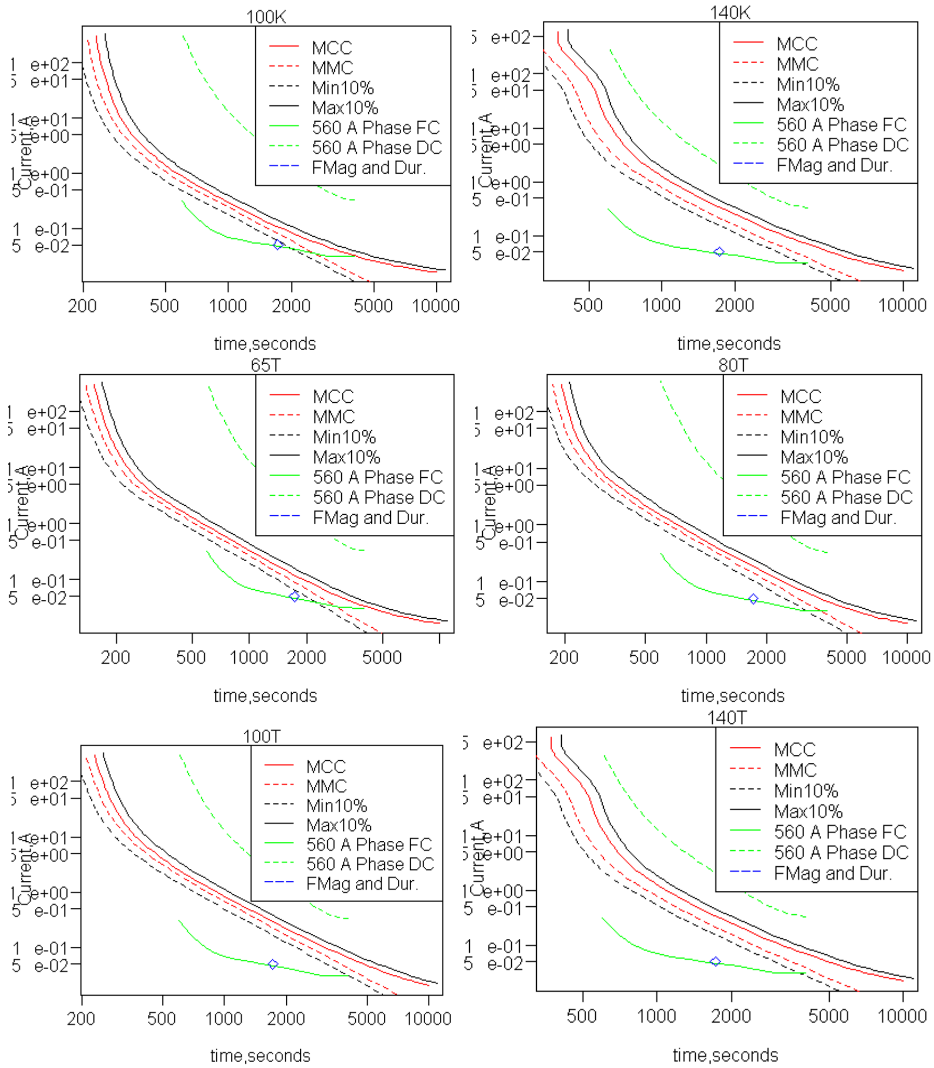

Figure A-4
Fuse and Phase Recloser TCC Curves

A second example of a fuse blowing scheme is shown in Figure A-5. The voltage and current waveforms where the fault occurred are plotted separately. The fuse TCC curves are plotted with the derived fault magnitude and duration shown as a diamond on the curve. The diamond falls between the minimum melting time and maximum clearing time curves.

A third example of a fuse saving scheme is shown in Figure A-6. The recloser fast and delayed TCC curves are plotted with the fuse TCC curves. The fuse TCC curves fall between the recloser fast and delayed curves. The description below the plots describes the system the user selected and the nominal voltage and load current based on the waveforms. The derived fault magnitude and duration are also included.

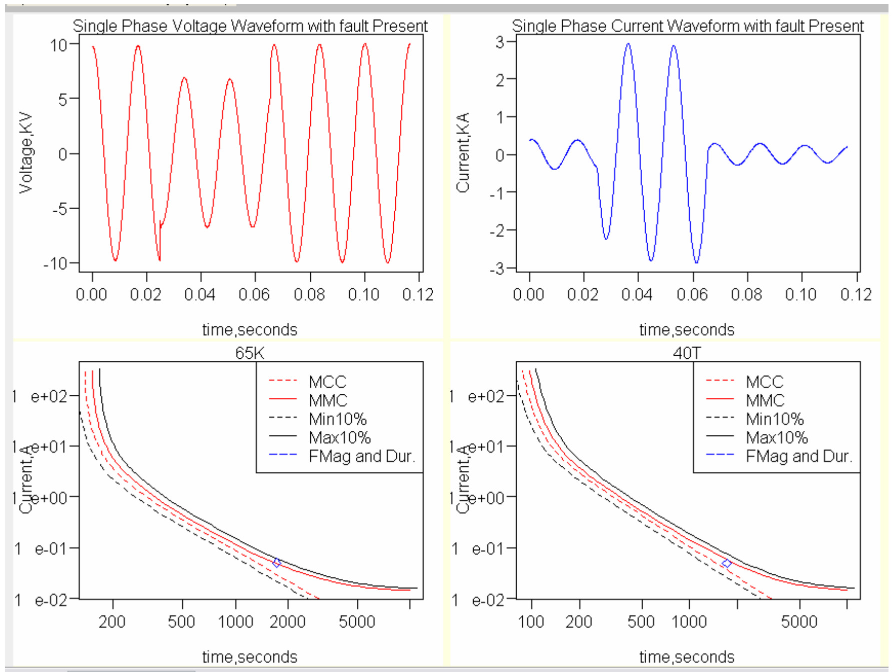

Figure A-5
Rpad Output for Fuse Blowing Scheme

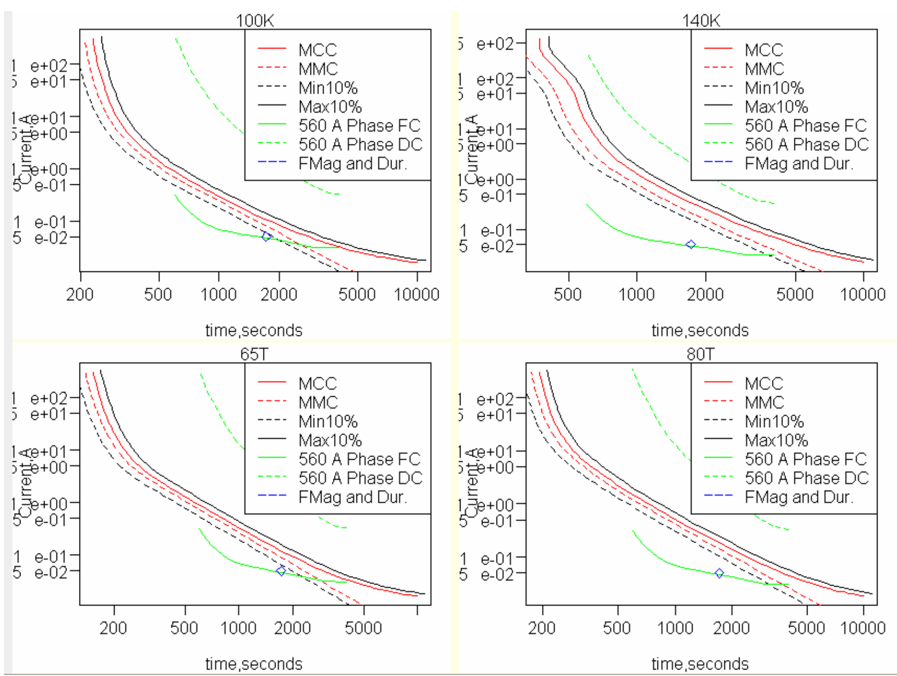

Figure A-6
Rpad Output for Fuse Saving Scheme

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