ARC FLASH MITIGATION: OVERVIEW OF CODEPENDENT SYSTEM STUDIES RELEVANT TO IEEE STANDARD 1584

A Thesis

Presented to

the Faculty of the Department of Electrical and Computer Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Electrical Engineering

by

Mainsah, Nyuykighan Karl Marvin

May 2015

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Finally, I dedicate this report to my loving parents and siblings; for the gift of life, the opportunity of an education and their unconditional love and support throughout my life.

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ABSTRACT

Accidents due to arc flash events are currently of special interest in the electrical power industry. These events often result in serious injuries, deaths, equipment damage, facility shutdowns, lawsuits, and penalties. Risk assessments are usually performed by the power systems engineer during the design phase to mitigate the effects of potential arc flash occurrences.

The objective of this thesis is to demonstrate the significance of arc flash hazard risk assessments implemented during the installation of electrical power equipment. This thesis presents a synopsis of the main industry design standards and codes that govern the design of electrical distribution systems in commercial and industrial facilities.

Simulations were performed for a case study using SKM Power Tools to demonstrate the interpretation and practical application of these standards and codes. Electrical studies and analyses were performed on the model, and recommendations were provided to address the mitigation of potential arc flash incidents throughout the electrical network of the case study.

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CHAPTER 1 INTRODUCTION & THESIS ORGANIZATION

INTRODUCTION

Recently enacted guidelines and regulations regarding arc flash hazards have focused industry attention on quantifying the dangers of arc flash events in energized low and medium voltage electrical equipment. Engineers and facility operators are now determining the correct arc flash boundaries and personal protective equipment (PPE) requirements to protect workers from arc flash dangers. As such, non-compliance observed by regulatory institutions such as the Occupational Safety and Health Administration (OSHA) lead to penalties such as fines and facility shutdowns.

The nature of explosive equipment failures and the rate of serious burn injuries in the electrical industry have been studied and the detailed investigation of the arc flash phenomena has led to the National Fire Protection Association (NFPA) to adopt arc flash guidelines for work on or near energized electrical equipment. IEEE Standard 1584, Guide for Performing Arc Flash Hazard Calculations provides detailed equations for determining arc flash energies.

Understanding the IEEE Standard 1584 is a key qualification for a Power System Design Engineer. Section 4 of this standard lists steps/procedure to conduct a comprehensive Arc Flash Hazard Study:

Step 1: Collect the System and Installation Data

Step 2: Determine the System Modes of Operation

Step 3: Determine the Bolted Fault Currents

Step 4: Determine the Arc Fault Currents

Step 5: Find Protective Device Characteristics and the Duration of Arcs

Step 6: Document the System Voltages and Classes of Equipment

Step 7: Select the Working Distances

Step 8: Determine the Incident Energy for All Equipment

Step 9: Determine the Flash-Protection Boundary for All Equipment

The three primary features of this procedure are – Short Circuit Study, Protective Device Coordination, & Arc Flash Study, which will be explored in this report. Arc flash hazard studies require knowledge of both the electrical power system facility, and the system's electrical protection. From the above listed steps, arc flash studies can therefore be considered a continuation of the short circuit and coordination aspects of a power system, since the results for each are required to assess arc flash hazards.

THESIS ORGANIZATION

Chapter 2: This section on Short Circuit Studies will cover topics like type, source and effects of faults. Short circuit calculation methods supported by a detailed computational example will also be introduced.

Chapter 3: This section on Power System Protection will be split into 2 parts; Part (I) Protective Devices: will cover the significance of power system protection, operation and application of common protective devices in low/medium voltage systems such as fuses, and relays; Part (II) Device

Coordination: will explore how the protection devices harmonize to isolate faults and protect vital components like cables, transformers, motors, generators, etc.. The theory of Time-Current Curves (TCCs) will be introduced. There would be examples showing protection and coordination principles using TCCs.

Chapter 4: This section on Arc Flash Studies will further elaborate on arc flash events at industrial facilities: history, nature, dangers, causes, governing standards, equipment labeling, etc. IEEE 1584 calculation methodology supported by a detailed computational example will also be introduced.

Chapter 5: CASE STUDY - The case study to complement this thesis will be the upgrade of the KAMAMA Pump Station, in Katia, Texana. The system will be modeled in *SKM Power Tools for Windows* and a comprehensive arc flash study based on the steps outlined in IEEE 1584 will be performed. The simulation will outline and compare results for various system configurations with the aim to identify the protective device settings for the safest arc flash energy category levels throughout the electrical system.

CHAPTER 2 SHORT CIRCUIT CURRENTS & FAULT ANALYSIS

2.1 INTRODUCTION – SHORT CIRCUIT CURRENTS

The operation of a power system departs from normal after the occurrence of a fault. Faults give rise to abnormal operating conditions-usually excessive currents and voltages at certain points on the system which are guarded against by various types of protective equipment – fuses, circuit breaker and relays [1].

These faults or short circuits occur once in a while due to lighting, flash over due to polluted insulation, falling of tree branches on the overhead system, animal intrusion and erroneous operations [8]. During the fault, the power system is called on to detect, interrupt and isolate these faults. The duty impressed on the equipment is dependent on the magnitude of the current, which is a function of the time of fault initiation [8].

For proper choice of circuit breakers and protective relaying, we must estimate the magnitude of currents that would flow under short circuit conditions—this is the scope of a fault analysis study [5]. Such calculations are performed for various types of fault such as three-phase, single line-to-ground fault, double line-to-ground fault, etc. [8]. In the view of sizing electrical installation and the required equipment, as well as determining the means required for the protection of life and property, short circuit currents must be calculated for every point in the electrical system [7]. This chapter is devoted to abnormal system behavior under conditions of symmetrical short circuit or three-phase fault and provide further understanding of the calculation methods essential when determining short circuit currents, even when computerized methods are employed [7].

2.2 NATURE OF SHORT CIRCUIT CURRENTS

2.2.1 Types Of Faults

A fault on a power system is an abnormal condition that involves an electrical failure of power system equipment operating at one of the primary voltages within the system [2]. Short-circuit faults can occur between phases, or between phases and earth, or both. Short circuits may be one-phase to earth (single line-to-ground), phase to phase (double line, line-to-line), two-phase to earth (double line-to-ground), three-phase clear of earth and three-phase to earth. The three-phase fault that symmetrically affects the three phases of a three-phase circuit is the only balanced fault whereas all the other faults are unbalanced [2].

The various types of short circuit faults are depicted in Figure 1 below. The frequency of occurrence decreases from part (a) to part (f):

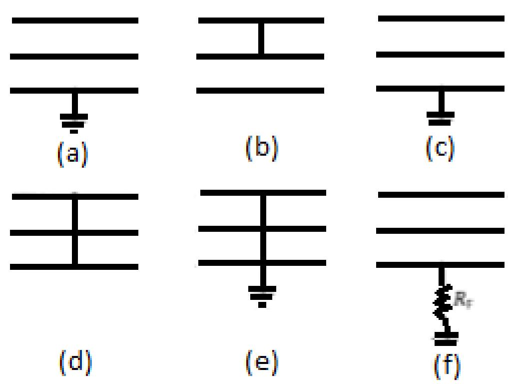


Figure 1: Types of Faults – from ref [1]

Experience has shown that between 70 and 80% of faults are single line-to-ground faults. About 15% are phase-to-phase faults. Roughly 5% of all faults involve all three phases [3, 7]. Though three-phase faults are rare, symmetrical fault analysis must be carried out, as this type of fault generally leads to most severe fault current against which the system must be protected [5].

2.2.2 Causes & Origin Of Faults

Open-circuit faults may be caused by the failure of joints on cables or overhead lines or the failure of all the three phases of a circuit-breaker or disconnector to open or close. For example, two phases of a circuit-breaker may close and latch but not the third phase or two phases may properly open but the third remains stuck in the closed position [2].

The vast majority of short-circuit faults are weather related followed by equipment failure. The weather factors that usually cause short-circuit faults are: lightning strikes, accumulation of snow or ice, heavy rain, strong winds, etc. [2].

Equipment failure, e.g., machines, transformers, reactors and cables, cause many short-circuit faults. These may be caused by failure of internal insulation due to ageing and degradation, breakdown due to high switching or lightning over voltages, by mechanical incidents or by inappropriate installation [2].

Short-circuit faults may also be caused by human error. A classic example is one where maintenance staffs inadvertently leave isolated equipment connected through safety earth clamps when maintenance work is completed. A three-phase to earth short-circuit fault occurs when the equipment is reenergized to return it to service [2].

2.2.3 Need For Power System Fault Analysis

Short-circuit calculations are generally performed for a number of reasons. These are briefly described below:

Health and Safety Considerations

Short-circuit fault analysis is carried out to ensure the safety of workers as well as the general public. Power system equipment such as circuit-breakers can fail catastrophically if they are subjected to fault duties that exceed their rating. Other equipment such as busbars, transformers and cables can fail thermally or mechanically if subjected to fault currents in excess of ratings [2].

Design, Operation and Protection of Power Systems

Short-circuit current calculations are made at the system design stage to determine the short-circuit ratings of new switchgear and substation infrastructure equipment to be procured and installed. In addition, calculations of minimum short-circuit currents are made and these are used in the calculation of protection relay settings to ensure accurate and coordinated relay operations [2].

Areas where short-circuit analysis is carried out is in the modification of an existing system or at the design stage of new electrical power installations such as a new offshore oil platform, new petrochemical process plant or the auxiliary electrical power system of a new power station [2].

Short circuit calculations should be done at critical points in the system. This would include: service entrance, panel boards, motor control centers, motor starters, transfer switches and load centers [9].

Design of Power System Equipment

Switchgear manufacturers design their circuit-breakers to ensure that they are capable of making, breaking and carrying, for a short time, the specified short circuit current. Manufacturers use the short circuit current ratings specified by their customers to ensure that the equipment is designed to safely withstand the passage of these currents for the duration specified [2].

2.2.4 Consequences Of Short-Circuits

The consequences are variable depending on the type and the duration of the fault; the point in the installation where the fault occurs and the short-circuit power. The consequences of faults can be *thermal* or *mechanical*:

Thermal effects

Short-circuit currents flowing through the conductors of various power system equipment create thermal effects on conductors and equipment due to heating and excess energy input over time as measured by I^2T where I is the short-circuit current magnitude and T is the short-circuit current duration [2]. At the fault location, the presence of electrical arcs can result in damage to insulation, welding of conductors or circuit breaker contacts, fire and possible danger to human life [7].

Mechanical effects

Short-circuit currents flowing through the conductors of various power system equipment create electromagnetic forces and mechanical stresses on equipment [2]. These electrodynamic forces result in deformation of the bus bars and disconnection of cables [7].

Other parts of the network may experience some abnormalities such as:

- Voltage dips during the time required to clear the fault, ranging from a few milliseconds to a few hundred milliseconds.
- Shutdown of a part of the network. The extent of the outage depends on the design of the network and the discrimination levels offered by the protection devices.
- Dynamic instability and/or the loss of machine synchronization.
- Disturbances in control / monitoring circuits, etc. [7].

2.3 SOURCES OF SHORT CIRCUIT CURRENTS

In modern power systems, there are various types of active sources that can contribute short-circuit currents in the event of short-circuit faults on the power system. These short circuit current contributions are from utility sources, generators, synchronous condensers and induction motors [8] - refer to Figure 2. Power system elements such as lines, cables, transformers, series reactors, etc., between the short-circuit fault location and the various current sources will affect the magnitude of the short-circuit currents that feed into the fault. The effect is generally to reduce the magnitude of the short-circuit currents and to increase the rate at which their ac and dc components will decay [2].

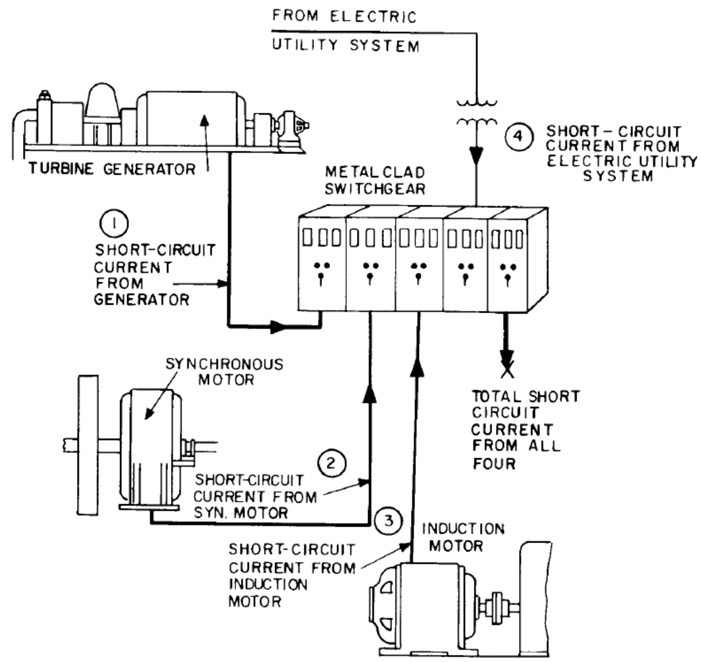


Figure 2: Sources Of Short Circuit Currents – from ref [8]

Utility Sources:

Utility represents the large interconnection of generators, transmission lines and load circuits. The transmission lines, distribution lines and transformers introduce impedance between the generator source and the fault point during a short circuit. The source voltage remains unaffected during fault conditions [8].

Generator Sources:

An in-plant generator contributes to a short circuit and the current decreases exponentially. The generator is driven by a prime mover and an exciter supplies the field; the steady state current will persist unless the circuit is open by a circuit breaker. The generator fault current is determined by three reactance values during various time frames:

Xd'' - Direct axis sub-transient reactance, during the first cycle

Xd' - Direct axis transient reactance, during 1 to 2 seconds

Xd - Direct axis reactance, during steady state

The total short circuit current (I_t) of a generator consists of an ac component (I_{ac}) and a dc component (I_{dc}). These components are given by equations 1 through 3. The ac component of the generator fault current is

$$I_{ac} = \left(\frac{1}{X_d^{"}} - \frac{1}{X_d'}\right) e^{\frac{-t}{Td^{"}}} + \left(\frac{1}{X_d'} - \frac{1}{X_d}\right) e^{\frac{-t}{Td'}} + \frac{1}{X_d} \ . \quad (1)$$

The dc component (I_{dc}) of the generator currents is

$$I_{dc} = (\sqrt{2})\left(\frac{1}{X_d}\right) e^{\frac{-t}{Td}} \ . \quad (2)$$

The total generator fault current (I_t) is

$$I_t = \sqrt{Iac^2 + Idc^2} \ . \quad (3)$$

Synchronous Motor & Synchronous Condenser:

The synchronous machines supply fault current like a synchronous generator. The fault current decays rapidly since the inertia of the motor and load acts as the prime mover with the field excitation maintained. The fault current diminishes as the motor/condenser slows down and the motor excitation decays [8].

Induction Motor Load:

The fault current contribution from an induction motor is due to the generator action produced by the load after the fault. The field flux of the induction motor is produced due to the stator voltage and hence the current contribution decays very rapidly upon fault clearing as the terminal voltage is removed [8].

Typical current waveforms during a short circuit are shown in Figure 3 and Figure 4 for various types of contributing sources.

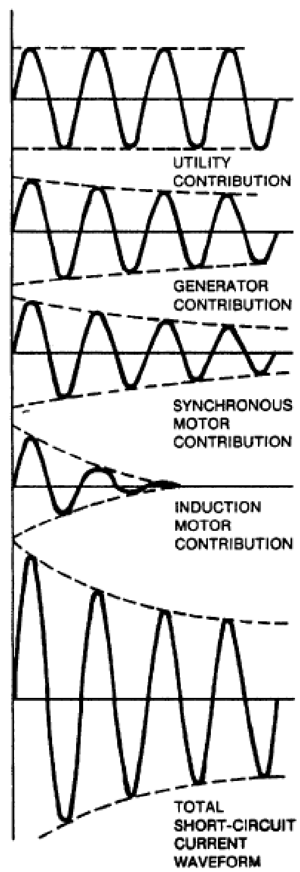


Figure 3: Decaying Short Circuit Current Waveforms – from ref [8]

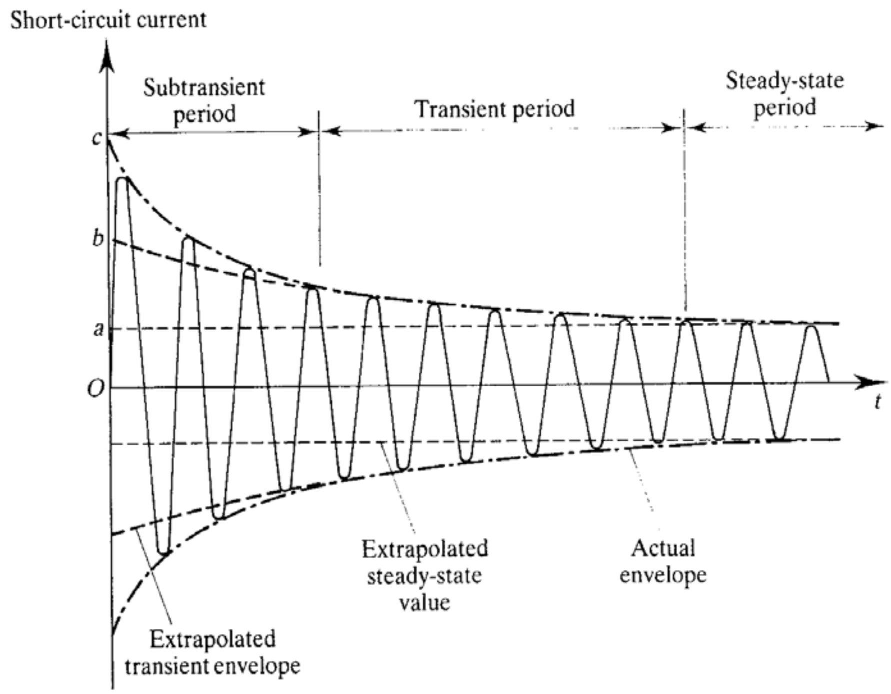


Figure 4: Short Circuit Armature Current In Synchronous Machine – from ref [5]

Total fault current as a function of time:

When a short circuit occurs in a system, the circuit impedance decreases appreciably. Therefore, the circuit current increases significantly as shown in Figure 5. During an asymmetrical fault, the total current can be treated as the sum of a dc current and a symmetrical ac component. The direct component eventually decays to zero as the stored energy in the system is expended in the form of I^2R loss. The direct current decay is inversely proportional to the X/R ratio of the system between the source and the fault. Therefore, it is important to analyze the short circuit current during the first cycle, the next several cycles and in the steady state [8].

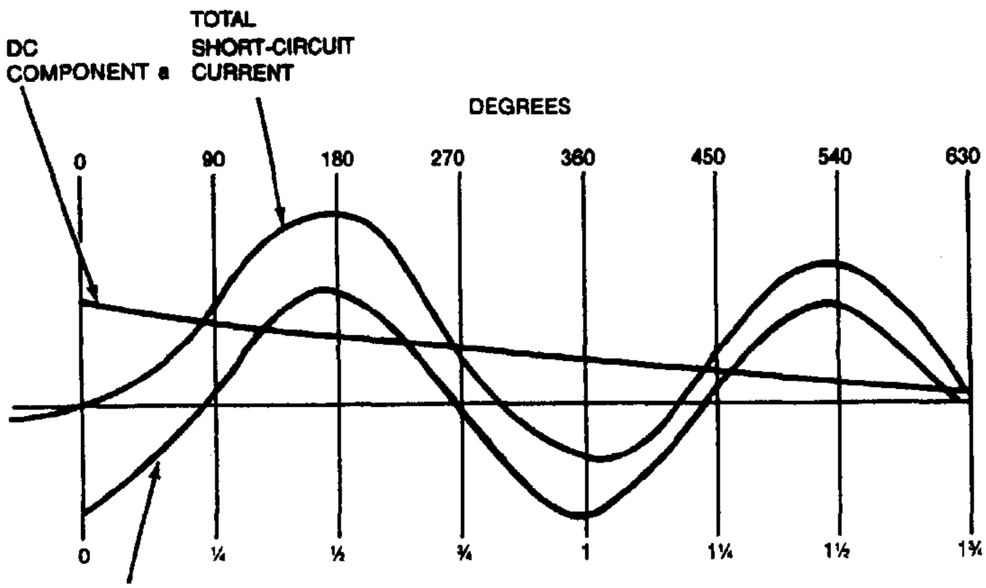


Figure 5: Total Fault Current Waveform – from ref [8]

2.4 CALCULATIONS OF SHORT CIRCUIT CURRENTS

2.4.1 Methods Of Fault Calculations

Normally, short circuit studies involve calculating a bolted three-phase fault condition. This can be characterized as all three-phases “bolted” together to create a zero impedance connection. This establishes a “worst case” (highest current) condition that results in maximum three phase thermal and mechanical stress in the system. From this calculation, other types of fault conditions can be approximated. This “worst case” condition should be used for interrupting rating, component protection and selective coordination. However, in doing an arc flash hazard analysis it is recommended to do the arc flash hazard analysis at the highest bolted three-phase short circuit condition and at the “minimum” bolted three-phase short circuit condition. There are several variables in a distribution system that affect calculated bolted 3-phase short-circuit currents [12].

Appendix I and Appendix II present a number of different methods used in short circuit calculations. These are accompanied by solved computational examples.

Appendix I - the Per-Unit method – from reference [9].

Appendix II- the ANSI method – from reference [27].

We observe from the above mentioned appendices that to determine the fault current at any point in the system, we first draw a one-line diagram showing all of the sources of short-circuit current feeding into the fault, as well as the impedances of the circuit components.

To begin the study, the system components, including those of the utility system, are represented as impedances in the diagram. The impedance tables include three-phase and single-phase transformers, cable, and busway. These tables can be used if information from the manufacturers if not readily available.

It must be understood that short circuit calculations are performed without current-limiting devices in the system. Calculations are done as though these devices are replaced with copper bars, to determine the maximum available short-circuit current. This is necessary to project how the system and the current limiting devices will perform. Also, multiple current-limiting devices do not operate in series to produce a “compounding” current-limiting effect. The downstream, or load side, fuse will operate alone under a short circuit condition if properly coordinated [12].

2.4.2 Computer-Aided Fault Analysis

There are several programs available to perform short circuit studies. These programs can be used to perform data-related operations such as [8]

- Convert the raw system data to a common base,
- Prepare one-line diagrams, and
- Determine system impedance for the calculation of momentary, interrupting, symmetrical and relay short circuit currents.

The input data to these programs can be entered interactively. The output of the short circuit study includes the following:

- Short circuit input data used in the network analysis.
- Calculations of three-phase, single line to ground fault, line to line and double line to ground fault currents. For the three-phase, four-wire system with a neutral conductor, the short circuit currents are required for the line to neutral short circuit.
- Calculation of appropriate circuit breaker current ratings based on ANSI or IEC standards.
- Some programs present the short circuit outputs in a one line diagram with the calculated values.
- Summary of currents at all the buses [8].

All computer programs designed to calculate short-circuit currents are predominantly concerned with (i) determining the required breaking and making capacities of switchgear and the electromechanical withstand capabilities of equipment; and (ii) determining the settings for protection relays and fuse ratings to ensure a high level of discrimination in the electrical network [7]. The user selects the necessary short circuit results at appropriate buses and compares the results with the circuit breaker ratings. Also, the short circuit currents are compared with the equipment short circuit ratings to ensure safe performance [8].

Short Circuit Input Data

To perform the software assisted fault calculations the following information must be obtained

- *Utility:* Nominal voltage, Utility three-phase and line-to-ground available contribution with associated X/R ratios i.e., 3-Phase and SLG MVA_{sc} available and X/R; or 3-Phase and SLG I_{sc} available and X/R ratio.
- *Cable:* Cable type, voltage rating, construction, size, #conductors per phase, length, impedance and conduit type.
- *Transformers:* MVA or KVA rating, transformer primary & secondary voltages, winding configurations, KVA rating, percent impedance (%Z) and X/R ratio on nominal MVA or KVA base.
- *AC Induction Motors:* Rated HP, Voltage, Full Load Amperes, Power Factor, Efficiency, Number of Poles, Rated Synchronous Speed (RPM).
- *Generators*: Base MVA or KVA Rating, Output Voltage, Synchronous Speed or Output Frequency (Hz), Number of Poles, Saturated Synchronous Reactance (Xd_v), Saturated Transient Reactance ($X'd_v$), Saturated Subtransient Reactance ($X''d_v$), Transient Time Constant (Td'), Subtransient Time Constant (Td"), and Armature Short Circuit Time Constant (Ta).

The complete list of information needed can be found in Appendix III – courtesy of BICE Engineering and Consulting. Remember, however, that all software, whatever its degree of sophistication, is only a tool. To ensure correct results, it should be used by qualified professionals who have acquired the relevant knowledge and experience.

CHAPTER 3 POWER SYSTEM PROTECTION

3.1 WHAT IS POWER SYSTEM PROTECTION?

Power system protection is the process of making the production, transmission, and consumption of electrical energy as safe as possible from the effects of failures and events that place the power system at risk. It is cost prohibitive to make power systems 100% safe or 100% reliable. As such, risk assessments are necessary for determining acceptable levels of danger from injury or cost resulting from damage.

Hence, the essence of power system protection is to safeguard the entire electrical system to maintain continuity of supply, to minimize damage and repair costs on affected equipment, and foremost to ensure safety of personnel [24]. Such an undertaking abides to the IEEE Code of Ethics in the appropriate application of technology consistent with the safety, health and welfare of the public, and to disclose promptly factors that might endanger the public or the environment.

3.2 BASIC REQUIREMENTS OF POWER SYSTEM PROTECTION

The requirements of protection are necessary for early detection and localization of faults, and for prompt removal of faulty equipment from service [24]. In order to carry out these duties, protection must have the following qualities:

- *Selectivity*: To detect and isolate the faulty item only.
- *Stability*: To leave all healthy circuits intact to ensure continuity or supply.

- *Sensitivity*: To detect even the smallest fault, current or system abnormalities and operate correctly at its setting before the fault causes irreparable damage.
- *Speed*: To operate speedily when it is called upon to do so, thereby minimizing damage to the surroundings and ensuring safety to personnel [24].

To meet all of the above requirements, protection must be reliable which means it must be

- *Dependable*: It *must* trip when called upon to do so, and
- *Secure*: It must *not* trip when it is not supposed to [24].

3.3 PROTECTIVE DEVICES

The fundamentals of power system protection are to determine the measurements of currents and/or voltages whether the power system is operating correctly. Different kinds of protective devices operate independently, co-dependently and simultaneously to maintain the integrity of the power grid. The basic components of system protection include: Voltage or Potential Transformers (PTs) and Current Transformers (CTs), Fuses, Circuit Breakers and Protective Relays.

The primary function of protective devices in a power system is to detect short circuits and isolate the fault by activating the appropriate circuit interrupting devices, which increases the reliability and safety of the electrical system. This thesis report focuses on the fundamental need-to-know information about Fuses and Protective Relays.

3.3.1 Protective Devices - Fuses

3.3.1.A Fuses – Introduction

The simplest of all circuit interrupting device is the fuse. Fuses are used when it is possible to use a simple and economic method protection against overcurrents and faults. They are fast to act when a major fault occurs and are reliable [6].

As an overcurrent protection device; it possesses an element that is directly heated by the passage of current and that is destroyed when the current exceeds a predetermined value. A suitably selected fuse should open the circuit by the destruction of the fuse element, eliminate the arc established during the destruction of the element and then maintain circuit conditions open with nominal voltage applied to its terminals (i.e., no arcing across the fuse element) [15].

The following information is required in order to select a suitable fuse for use on the distribution system: voltage and insulation level, type of system, maximum short-circuit level, and load current. These four factors determine the fuse nominal current, voltage and short circuit capability characteristics [15]. The characteristics of fuses vary widely depending upon the application. The main parameters concerning an application are [6]

- Rated voltage
- Rated current
- Rated frequency
- AC and DC service and type of load current
- Time versus current characteristic
- Time versus I^2t characteristic
- Rated breaking capacity

- Rated power dissipation of the fuse
- Cut-off current in AC service
- Pre-arcing and arcing times
- Dimension

Modern fuses have different characteristics, and it is no longer satisfactory to just specify a voltage and current rating for them [14]. Fuse manufacturers are able to vary the shape and steepness of the characteristics by carefully designing the shape of the fuse element, by surrounding the element with different heat removing media and by selecting different fusable metals and alloys [6]. Each type must be studied so that the application of fuses is done with full knowledge of their respective characteristics [14].

3.3.1.B Fuse Design And Operation

Fuse design includes both sensing and interrupting elements. Fuses responds to the combination of magnitude and duration of circuit current flowing through them. A fuse can carry continuous current, and, therefore, when this current exceeds its rated continuous current due to any fault, it responds to de-energize and interrupt the affected phase or phases of the circuit or equipment that is faulty.

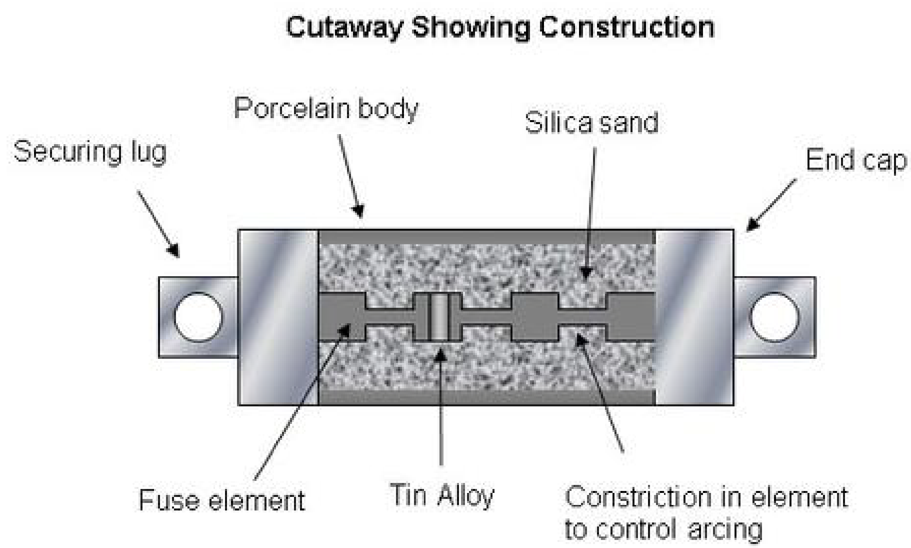


Figure 6: Cross Section of a Current Limiting Fuse – from ref [60]

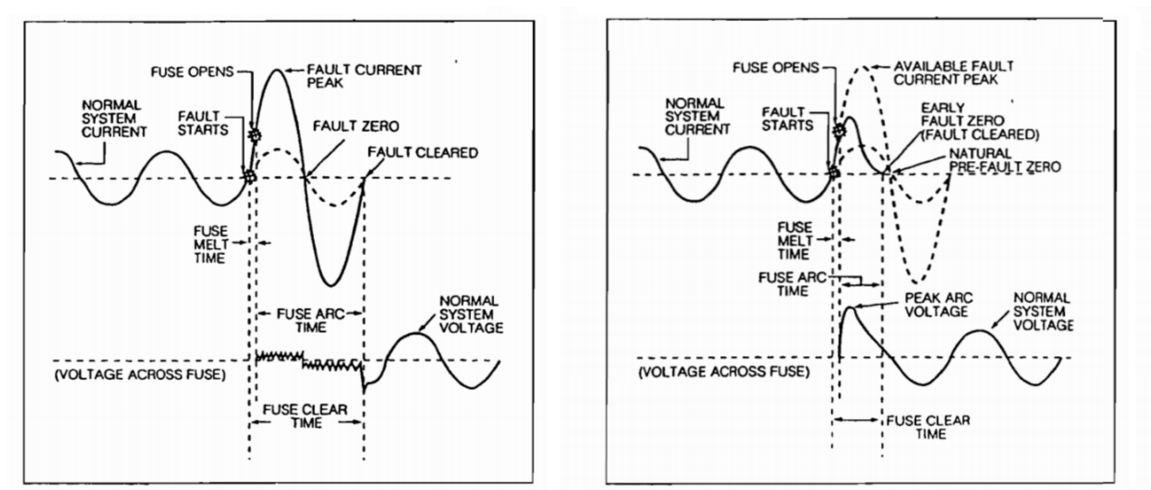
The mechanism of interruption is performed by two processes: thermal process and interrupting process [17].

Thermal Process

The current-responsive element in the fuse is sensitive to the current flowing through it. Its temperature rises when heat is generated as a result of the current flow. For a current less than or equal to the fuse rated continuous current, the fuse is in a stable condition where the heat generated equals the heat dissipated. When a current higher than rated continuous current flows through the fuse with sufficient magnitude, it causes the current-responsive element to melt before other steady-state temperature conditions are achieved [17].

Interrupting Process

The current continues to flow through an arc after the current-responsive element melts. The arcing takes some time until the current is interrupted. It is called “arcing time” and is defined as “the time elapsing from the melting of the current - responsive element to the final interruption of the circuit [17]". The arcing period in the interrupting process is added to the melting process time in the thermal process to give the total clearing time. The characteristic development of current and voltage during the operation of a fuse is shown in Figure 7 below:



Current and Voltage Waveforms for an Expulsion Fuse Operation **Current and Voltage Waveforms for a Current-Limiting Fuse Operation**

Figure 7: Current and Voltage waveforms during fuse operation – from [65]

From Figure 7, we observe the maximum instantaneous current through the fuse during total clearing time (peak let-through current) which is much less than the possible peak passing without the fuse. Fuse let-through charts are used to determine the prospective fault current that will be available at the load side of the fuse. The brief description of the application of fuse let-though charts is presented in reference [16]. An example of a fuse let-through chart is shown in Figure 8.

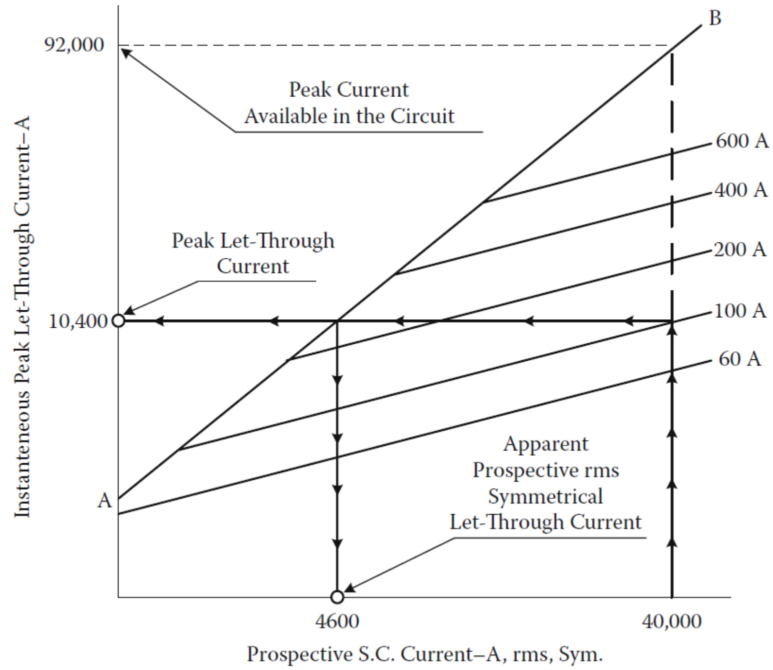


Figure 8: Fuse Let-Through Chart – from ref [20]

In summary, the operating sequence of a fuse (illustrated in Figure 9) is

1. The fuse element heats up and finally melts,
2. As soon as melting occurs a gap is formed at one or more points along the element,
3. An arc is then established across each gap,
4. The heat of the arc further melts the ends of the elements at each gap and so the gap is increased,
5. Hence the arc length increases and the arc becomes weaker. A point is reached when the arc becomes unstable and cannot be maintained and,
6. The arc is extinguished and the circuit is isolated by the fuse.

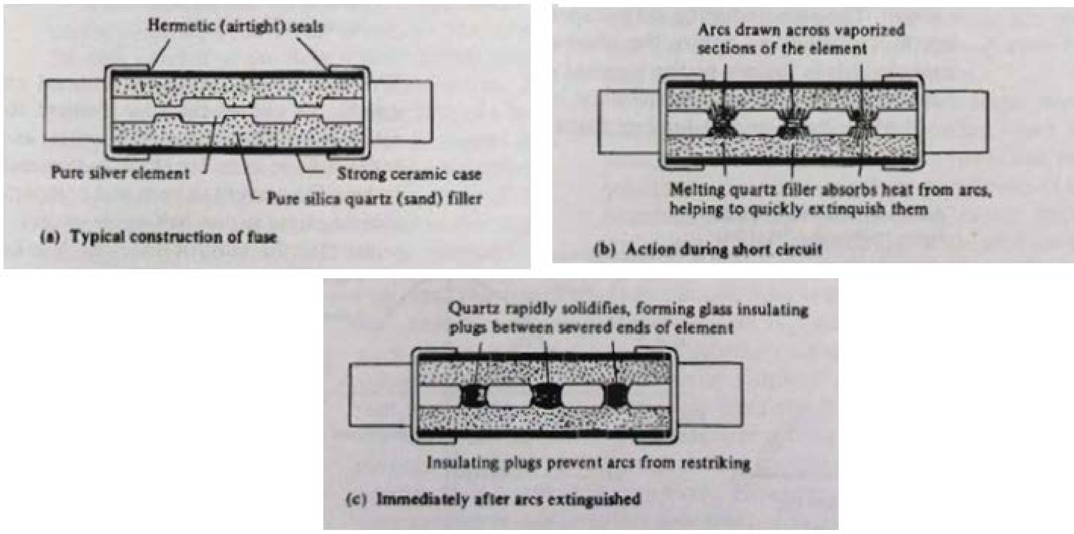


Figure 9: Construction & Operation of Current-Limiting Fuses – from ref [14]

3.3.1.C Fuse Types And Classification

Fuses are classified into *Power-Class* and D*istribution-Class* fuses. Power-Class fuses have specifications based on particular requirements for generating sources and substations. The specifications of Distribution-Class fuses are more closely matched with requirements of distribution systems. Some of these specifications in accordance with American National Standards Institute (ANSI) Standard for the two classes are given in Table 1.

Table 1: Comparison of ANSI Fuse Specifications – from ref [17]

Comparison of ANSI Fuses Specifications

Requirements	ANSI C37.42 Distribution Cutouts and Fuse Links	ANSI C37.44 Cutouts and Fuse Links	ANSI C37.46 Power Fuses	ANSI C37.47 Distribution Current-Limiting Fuses
Rated kV	2.6–38	2.5–15	2.8–169	2.8–27
Rated continuous current (A)	To 200	To 200	To 700	To 200
Rated interrupted current (kA)	2.6–16	2.2–7.1	1.25–80	12.5–50
(*X*/*R*) ratio at maximum interrupting current	1.33–15	2.3–12	≥15	≥10

Fuses are produced in many shapes and sizes, and various types are illustrated in Figure 10.

A range of low-voltage fuselink types: (2) general purpose industrial fuselinks (3) fuselinks for domestic purposes (4) fuselinks for protecting semiconductors (5) fuselinks for use in UK electricity supply networks and (6) compact fuselinks for industrial applications

Figure 10: Range Of Low-Voltage Fuselink Types – from ref [13]

Another classification of fuses is based on interrupting characteristics. The fuses are classified into *Current-Limiting* fuses and *Expulsion* fuses (non-current-limiting).

Expulsion Fuses

These are also called *Zero-Current-Clearing* fuses*;* since the fuse must wait until the current passes through zero before successful clearing is accomplished. An expulsion fuse is a vented fuse in which the expulsion effect of the gases produced by internal arcing, either alone or aided by other mechanisms, results in current interruption. An expulsion fuse is not current limiting and as a result limits the duration of a fault on the electrical system, not the magnitude [18].

Current-Limiting Fuse (CLF)

A current limiting fuse is a fuse that when its current-responsive element is melted by a current within the fuse's specified current limiting range, abruptly introduces a high resistance to reduce current magnitude and duration, resulting in subsequent current interruption. This type of fuse is basically different from the *zero-current* waiting types. Here the principle is called current limiting or energy limiting. It does this by introducing a high resistance into the circuit. This limits the current, but it also improves the power factor, making the current more in phase with the voltage. The mechanism of the operation of current-limiting fuses is discussed in Section 3.3.1.B.

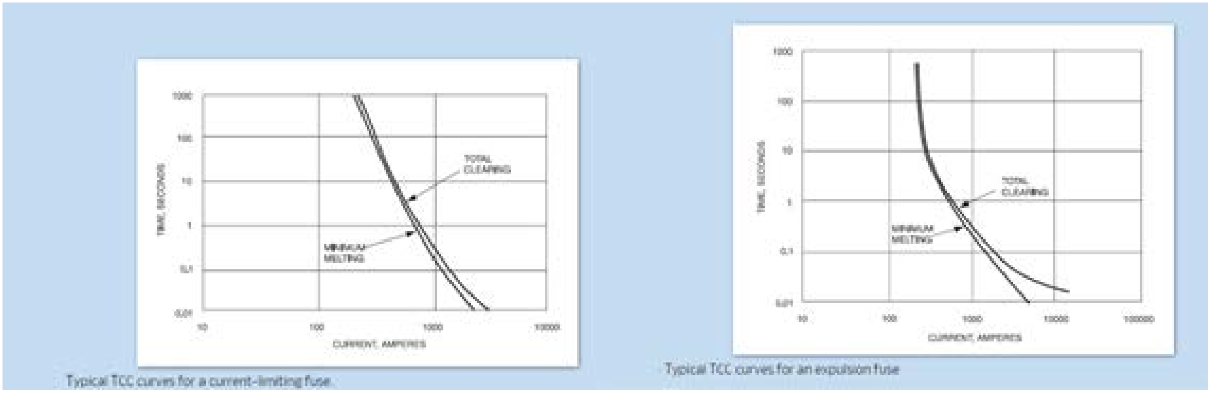


Figure 11: TCC Current-Limiting (Left) And Expulsion Fuse (Right) – from ref [61]

There are three types of current-limiting fuses:

- *Backup CLF:* A fuse capable of interrupting all currents from the maximum rated interrupting current down to the rated minimum interrupting current [19].
- *General Purpose CLF:* A fuse capable of interrupting all currents from the maximum rated interrupting current down to the current that causes melting of the fusible element in one hour [19].
- *Full Range CLF:* A fuse capable of interrupting all currents from the rated interrupting current down to the minimum continuous current that causes melting of the fusible element(s), with the fuse applied at the maximum ambient temperature specified by the manufacturer [19].

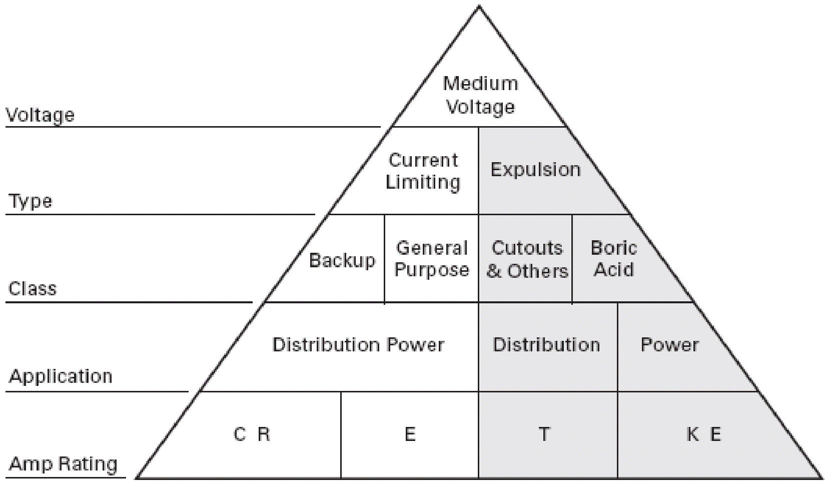


Figure 12: Classification of Fuses – from ref [62]

Current-limiting fuses are very good at clearing high-current faults. They have a much harder time with low-current faults or overloads. For a low level fault, the fusible element will not melt, but it will get very hot and can melt the fuse hardware resulting in failure. This is why the most common CLF application is as a backup in series with an expulsion fuse. The expulsion fuse clears low level faults, and the CLF clears high-current faults [19]. Note: These descriptions are by no means complete, and the engineer should consult the manufacturers for fuses required for special system protection applications.

3.3.1.D Miscellaneous: Fuse-Fuse Coordination

The essential criterion when using fuses is that the maximum clearance time for a main fuse should not exceed 75% of the minimum melting time of the back-up fuse, as indicated in Figure 13 and Figure 14. This ensures that the main fuse interrupts and clears the fault before the back-up fuse is affected in any way. The factor of 75% compensates for effects such as load current and ambient temperature, or fatigue in the fuse element caused by the heating effect of fault currents that have passed through the fuse to a fault downstream but that were not sufficiently large enough to melt the fuse [15].

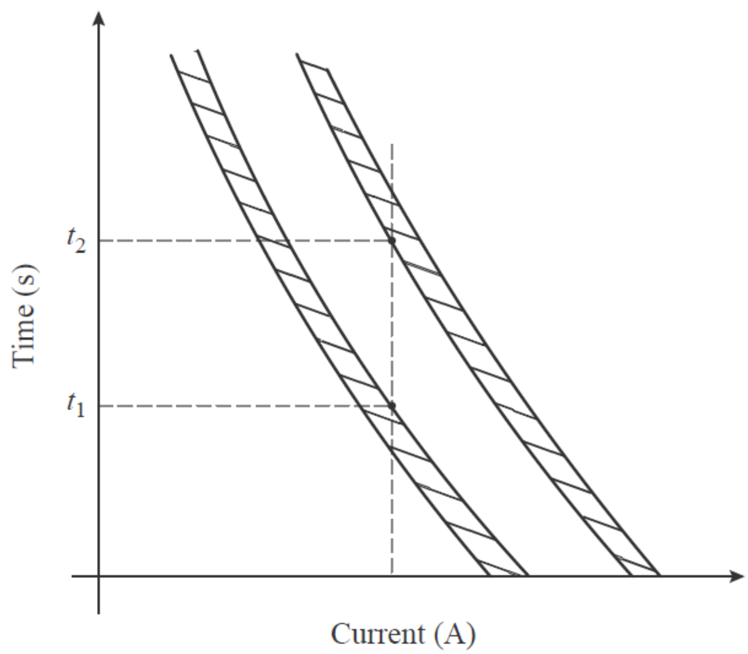


Figure 13: Criteria For Fuse-Fuse Coordination $t_1 < 0.75t_2$ – from ref [15]

For coordination at higher currents than are shown on published time-current characteristics (operations faster than 0.01 sec), ensure that the maximum clearing I^2t of the load-side fuse is less than 75% of the minimum melt I^2t of the source-side fuse. Manufacturers provide both of these I^2t values for current-limiting fuses [19].

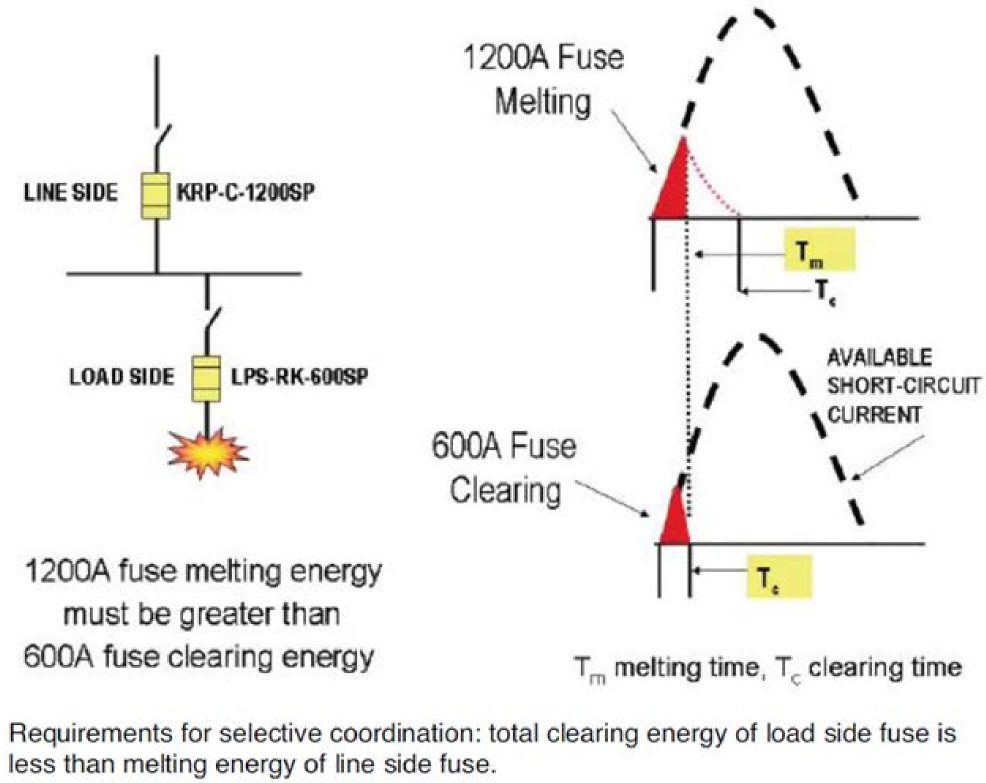


Figure 14: Coordination Of Low-Voltage Current-Limiting Fuses – from ref [12]

The coordination of fuses of the same manufacturer is fairly straightforward. Most manufacturers provide coordination chart or selectivity ratio guide for use with their fuses – refer to Table 2 - courtesy of *Cooper Bussmann EATON.* Figure 15 is for illustrative purposes and should not be used in actual studies. Note: The term *lineside* or protecting link means the fuse that is closest to the source and *loadside* or protected link means the fuse that is closes to the fault.

Table 2: Selectivity Ratio Guide – from ref [12]

Selectivity Ratio Guide (Lineside to Loadside)[1]

Lineside Fuse: Current Rating	Type	Trade Name (Class)	Bussmann Symbol	601-6000A Time-Delay Low-Peak (L) KRP-C_SP	601-4000A Time-Delay Limitron (L) KLU	0-600A Dual-Element Time-Delay Low-Peak (RK1) LPN-RK_SP LPS-RK_SP	0-600A Dual-Element Time-Delay Low-Peak (J) LPJ-SP TCF	0-600A Dual-Element Time-Delay Fusetron (RK5) FRN-R FRS-R	601-6000A Fast-Acting Limitron (L) KTU	0-600A Fast-Acting Limitron (RK1) KTN-R KTS-R	0-1200A Fast-Acting T-Tron (T) JJN JJS	0-600A Fast-Acting Limitron (J) JKS	0-60A Time-Delay SC (G) SC	0-30A (CC) LP-CC FNQ-R KTK-R
601 to 6000A	Time-Delay	Low-Peak (L)	KRP-C_SP	2:1	2.5:1	2:1	2:1	4:1	2:1	2:1	2:1	2:1	2:1	2:1
601 to 4000A	Time-Delay	Limitron (L)	KLU		2:1									
0 to 600A	Dual-Element	Low-Peak (RK1) (J)	LPN-RK_SP LPS-RK_SP LPJ-SP TCF	–	–	2:1	2:1	8:1	–	3:1	3:1	3:1	4:1	2:1
		Fusetron (RK5)	FRN-R FRS-R	–	–	1.5:1	1.5:1	2:1	–	1.5:1	1.5:1	1.5:1	1.5:1	2:1
601 to 6000A	Fast-Acting	Limitron (L)	KTU	2:1	2.5:1	2:1	2:1	6:1	2:1	2:1	2:1	2:1	2:1	2:1
0 to 600A	Fast-Acting	Limitron (RK1)	KTN-R KTS-R	–	–	3:1	3:1	8:1	–	3:1	3:1	3:1	4:1	
0 to 1200A	Fast-Acting	T-Tron (T)	JJN JJS	–	–	3:1	3:1	8:1	–	3:1	3:1	3:1	4:1	
0 to 600A	Fast-Acting	Limitron (J)	JKS	–	–	2:1	2:1	8:1	–	3:1	3:1	3:1	4:1	
0 to 60A	Time-Delay	SC (G)	SC	–	–	3:1	3:1	4:1	–	2:1	2:1	2:1	2:1	

1. Where applicable, ratios are valid for indicating and non-indicating versions of the same fuse. At some values of fault current, specified ratios may be lowered to permit closer fuse sizing. Consult with Bussmann. Ratios given in this Table apply only to Bussmann fuses. When fuses are within the same case size, consult Bussmann.

NOTE: All the fuses in this table have interrupting ratings of 200kA or greater, except the SC fuses have 100kA IR.

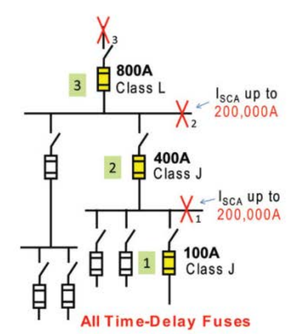


Figure 3: Example to Evaluate Fuse Selective Coordination

Each fuse manufacturer has table only for their brands. Do not mix fuses of different manufacturers	Load-side: 601-6000A Class L Time-Delay	Load-side: 0-600A Class J Time-Delay	Load-side: 0-600A Class RK1 Time-Delay	Load-side: 0-600A Class RK5 Time-Delay
Line-side Fuse: 601-6000A Class L Time-Delay	2:1	2:1	2:1	4:1
Line-side Fuse: 1-600A Class J Time-Delay	-	2:1	2:1	8:1
Line-side Fuse: 1-600A Class RK1 Time-Delay	-	2:1	2:1	8:1
Line-side Fuse: 1-600A Class RK5 Time-Delay	-	1.5:1	1.5:1	2:1

Notes: 1. Fuses in this table have interrupting rating of 200 kA.
2. Selective coordination assured if amp rating ratio between line-side fuse and load-side fuse is equal or greater than the ratio shown.

Table 1: Fuse Selectivity Amp Rating Ratio Guide

Analysis for Figure 3 using Table 1

Investigate the circuit for fuses 1, 2, and 3 in figure 3 using the Selectivity Amp Rating Ratio Table method.

1. Check fuse 1 with fuse 2

• For the actual fuses, the line-side to load-side amp rating ratio is 400 A:100 A = 4:1
• Both fuse 1 and fuse 2 are Class J time-delay and Table 1 shows a ratio of 2:1 or greater is necessary.
• Therefore since the actual amp rating ratio for fuse 1 and fuse 2 (4:1) is equal or greater than 2:1 (Table 1), fuse 1 will selectively coordinate with fuse 2 for any overcurrent up to 200 kA.

2. Check fuse 1 with fuse 3

• Actual amp ratio is 800 A:100 A = 8:1
• 2:1 or greater is necessary (Table 1).
• Fuse 1 selectively coordinates with fuse 3 up to 200 kA.

3. Check fuse 2 with fuse 3

• Actual amp rating ratio is 800 A:400 A = 2:1
• 2:1 or greater is necessary (Table 1).
• Fuse 2 will selectively coordinate with fuse 3 for any overcurrent up to 200 kA.

Figure 15: Illustration of Fuse Selectivity Ratio Guide – from ref [63]

3.3.2 Protective Devices – Relays

3.3.2.A Relays – Introduction

A relay is a device which makes a measurement or receives a signal which causes it to operate and to effect the operation of other equipment [22]. A protective relay monitors system conditions (e.g., amps, volts, etc., using CTs and PTs) and reacts to the detection of abnormal conditions. The relay compares the real-time actual quantities against preset programmable threshold values and sends dc electrical control signals to trip circuit breakers or other opening devices in an effort to clear an abnormal condition on the equipment it is protecting. When system problems are detected and breakers are tripped, alarm indications are sent to system control and sometimes other protection operations are initiated. As a result, equipment may be de-energized, taken off-line, and consumers will be out of power with minimal equipment damage [22].

3.3.2.B Classification Of Relays

Protection relays can be classified in accordance with their construction, the incoming signal and function - see Table 3.

Table 3: Classification of Relays – from ref [15]

CONSTRUCTION	INCOMING SIGNAL	FUNCTION
**Electromechanical*	Current	**Overcurrent*
Solid State	Voltage	Directional Overcurrent
Microprocessor	Power	Distance
Numerical	Frequency	Overvoltage
Non-Electrical (Thermal, Pressure)	Temperature	Differential
	Pressure	Reverse Power
	Speed	

This report covers the fundamentals of *electromechanical relays* and *overcurrent relays*.

3.3.2.C Basics Of Relay Operation

A typical relay circuit is shown in in Figure 16. This diagram shows one phase of a three-phase system for simplicity. The relays circuit connections can be divided into three parts:

i) First part is the primary winding of a current transformer CT, connected in series with the line to be protected,

ii) Second part consists of secondary winding and relay operating coil; and,

iii) Third part is the tripping circuit which may be either ac or dc. It consists of a source of supply, the trip coil of the circuit breaker and the relay stationary contacts.

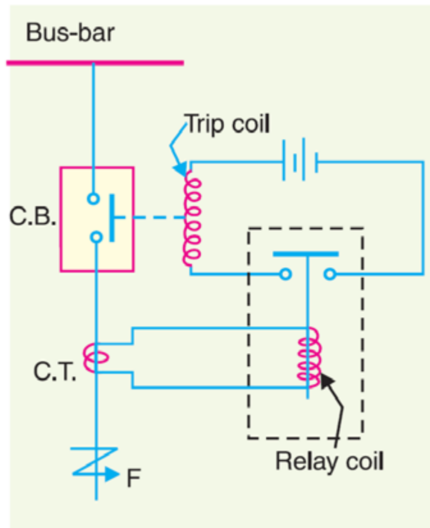


Figure 16: Basic Functionality Of Relay Operation – from ref [23]

When a short-circuit occurs at point F on the line, the current flowing in the line increases to an enormous value. This results in a heavy current flow though the relay coil, causing the relay to operate by closing its contacts. This in turn closes the trip circuit of the beaker, making the circuit breaker to open and isolating the fault section from the rest of the system. In this way, the relay ensures the safety of the circuit equipment from damage and normal working of the healthy portion of the system [23].

3.3.2.D Electromechanical Relays

Most of the relays in service on electric power systems today are electromechanical type. These relays are constructed with electrical, magnetic and mechanical components and have an operating coil and various contacts, and are very robust and reliable. They are also referred to as electromagnetic relays due to their magnetic components [15]. They work on two main operating principles: Electromagnetic attraction and Electromagnetic induction.

Electromagnetic Attraction Principle

Many relays are based on electromagnetic attraction principle and most of them are solenoid relays. The main element of these relays is a solenoid wound around an iron core and steel plunger or armature that moves inside the solenoid and supports the contacts [17]. Figure 17 shows the schematic arrangement of the solenoid type relay.

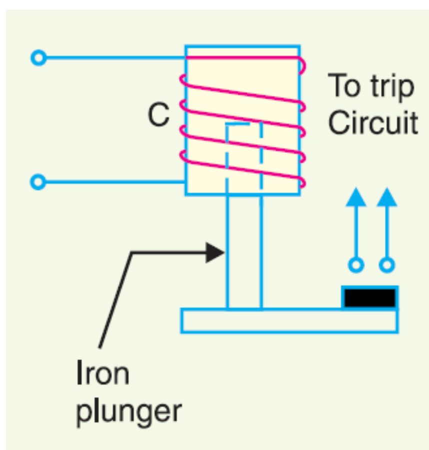


Figure 17: Relay Operation – Electromagnetic Attraction Type – from ref [23]

Under normal operating conditions, the current through the relay coil *C* is such that it holds the plunger by gravity or spring in the position shown. However, on the occurrence of a fault the current though the relay coil becomes more than the pickup value, causing the plunger to be attracted to the solenoid. The upward movement of the plunger closes the trip circuit, thus opening the circuit breaker and disconnecting the faulty circuit [23]. These relays operate without any intentional time delay, usually within one-half cycle. They are called "instantaneous overcurrent relays" and operate with a definite-current characteristic [17].

Electromagnetic Induction Principle

An induction relay works only with alternating current [15]. Construction of an induction disk relay is similar to a watt-hour meter since it consists of an electromagnet and a movable armature (metal disk) on a vertical shaft restrained by coiled spring [17]. The general arrangement of this type of relay is shown in Figure 18.

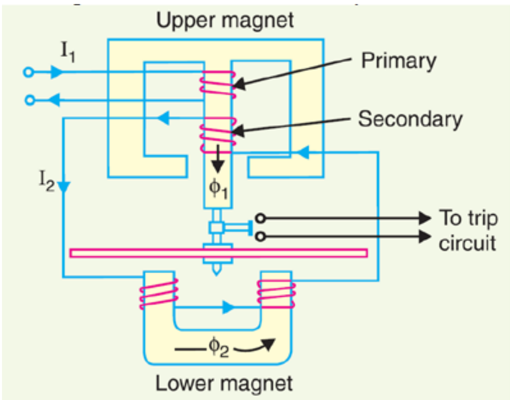


Figure 18: Relay Operation – Electromagnetic Induction Type – from ref [23]

It consists of a pivoted aluminum disc arranged to rotate freely between the poles of two electromagnets. The upper electromagnet carries two windings, the primary and the secondary. The primary winding carries the relay current I_1 while the secondary winding is connected to the winding of the lower magnet.

The primary current induces e.m.f. in the secondary and so circulates I_2 in it. The flux Φ_2 induced in the lower magnet by the current in the secondary winding of the upper magnet will lag behind Φ_1 by an angle θ. The two fluxes Φ_1 and Φ_2 differing in phase by α will produce driving torque T on the disc proportional to $\Phi_1\Phi_2\sin\theta$ [23]. The rotating motion of the disc closes the gap between the moving and fixed contacts to finally initiate the circuit breaker tripping operation.

Assuming the fluxes to be proportional to the current in the relay coil, the driving Torque T is proportional to the square of the current in the relay coil.

$T \;\alpha\; \Phi_1\Phi_2\sin\theta$
$T \;\alpha\; I^2\sin\theta$

Therefore the speed of the disc is proportional to I^2. The classical expression of speed is

$$Speed = \frac{Distance}{Time}. \tag{4}$$

Thus, we observe that Speed α 1/Time.
Speed α I^2.
1/Time α I^2.
Time α $1/I^2$.

It can be seen that the operating time of an induction relay is inversely proportional to a function of current, i.e., it has a long operating time at low multiples of setting current and a relatively short operating time at high multiples of setting current. This means two adjustments are possible on the relay, namely: The current pick-up or plug setting and the time multiplier setting [24].

Pick-Up Current

It is the minimum current in the relay coil at which the relay starts to operate. So long as the current in the relay is less than the pick-up value, the relay does not operate and the breaker controlled by it remains in the closed position. However, when the relay coil current is equal to or greater than the pick-up value, the relay operates to energize the trip coil which opens the circuit breaker [23]. The pick-up current of a relay is the product of the rated secondary current of the CT and its current or plug setting.

Current or Plug Setting (PS)

It is often desirable to adjust the pick-up current to any required value. This is known as Current or Plug Setting. [23]. The Plug setting on the relay varies the effective turns in the upper electromagnet [24]. This changes the torque on the disc and hence the time of operation of the relay [23]. The Pick-up Setting value is usually referred to as the Plug Setting Multiplier (PSM).

The Plug Setting of the relay is

$$PS = \frac{(Overload\ factor)(Nominal\ Current)}{CT\ Ratio}, \qquad (5)$$

and the Plug Setting Multiplier is

$$PSM = \frac{Actual\ secondary\ current}{relay\ current\ setting} = \frac{I_{relay}}{PS} = \frac{Fault\ Current}{(CT\ Ratio)(PS)}\ . \quad (6)$$

where I_{relay} is the current through the relay operating coil [15, 23, 25].

The value of PSM tells us about the severity of the current as seen by the relay. A PSM < 1 means that normal load current is flowing. At PSM > 1, the relay is supposed to pick up. Higher values of PSM indicate how serious the fault is [25]. Note that in relay setting calculations, $1 \le PSM \le 20$.

Time Multiplier Setting (TMS)

Also referred to as Time-Setting Multiplier or Time Dial Setting. The time dial setting adjusts the time delay before the relay operates whenever the fault current reaches a value equal to, or greater than, the relay current setting. In electromechanical relays, the time delay is usually achieved by adjusting the physical distance between the moving and fixed contacts; a smaller time dial value results in shorter operating times [15].

The effect of altering the TMS is to move the relay characteristic vertically. Changing both PS and TMS results in moving the relay characteristic both horizontally and vertically – refer to Figure 19.

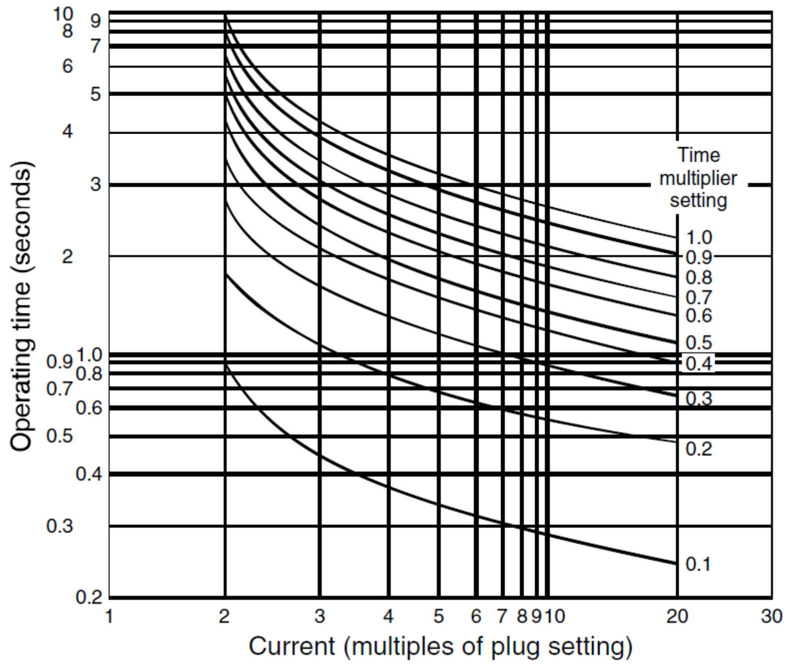


Figure 19: Effect Of Plug Setting and Time Multiplier Setting – from ref [24]

3.3.2.E Overcurrent Relays

The operating current for all overcurrent relays is either fixed or adjustable. The relay contacts close and initiate the circuit breaker tripping operation when the current flowing from the secondary of CT to the relay exceeds a given setting [17]. On the basis of the relay operating characteristics, overcurrent relays can be classified into three groups: *definite current or instantaneous, definite time* and *inverse time.* The characteristic curves of these three types are shown in Figure 20 which also illustrates the combination of an instantaneous relay with one having an inverse time characteristic [15].

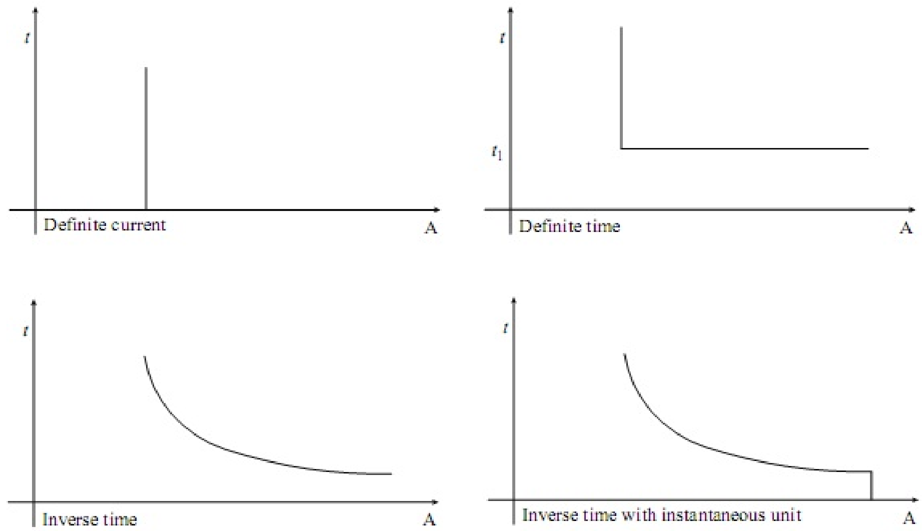


Figure 20: Operating Characteristics of Overcurrent Relays – from ref [15]

Definite Current or Instantaneous Relays - ANSI Code #50

It is to be noted that the word *instantaneous* has a different connotation in the field of power system protection. *Instantaneous* actually means *no intentional time delay*. Howsoever fast we want the relay to operate; it needs a certain minimum amount of time. Definite Current type relays operate on the principle of electromagnetic attraction, with an operating time in the order of a few milliseconds. Such a relay has only the pick-up setting and does not have any time setting – operates instantaneously when the current reaches or exceeds the setting threshold or pre-determined value [25]. The characteristic curve of a definite current relay is shown in Figure 21.

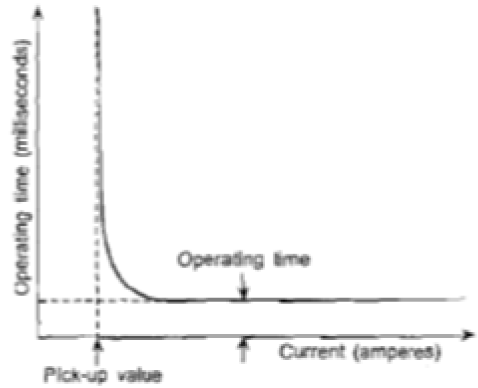


Figure 21: Definite Current Relay Characteristic – from ref [25]

Definite Time Relays

A definite time overcurrent relay can be adjusted to issue a trip output at a definite (and adjustable) amount of time, after it picks up. Thus, it has a time-setting adjustment and a pick-up adjustment. [25]. It should be noted that the time-delay setting is independent of the value of the overcurrent required to operate the relay [15]. The characteristic curve of a definite time relay is shown in Figure 22.

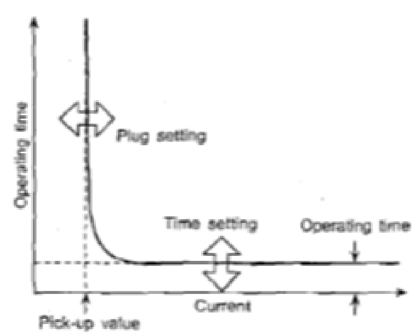


Figure 22: Definite Time Relay Characteristic – from ref [25]

Inverse Time Relays - ANSI Code #51

Inverse-time relays are also referred to as inverse definite minimum time (IDMT) overcurrent relays. The fundamental property of these relays is that they operate in a time that is inversely proportional to the fault current [15]. Inverse time characteristic fits in very well, with the requirement that the more severe a fault is, the faster it should be cleared to avoid damage to the apparatus. This type of characteristic is naturally obtained from an electromechanical relay, which has led to its widespread use and standardization [25]. The characteristic curve of an IDMT relay is shown in Figure 23.

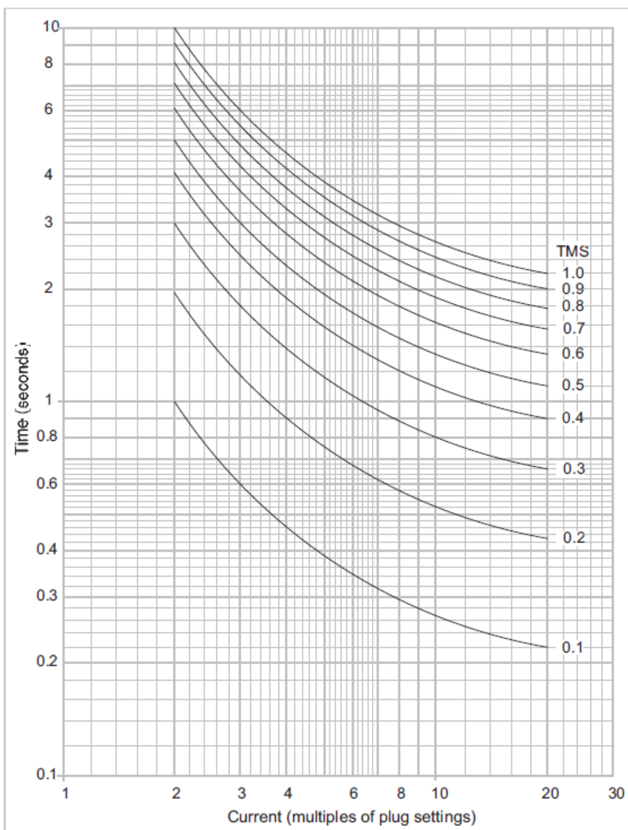


Figure 23: Typical Time-Current Characteristics of IDMT Relay – from ref [26]

The current/time tripping characteristics of IDMT relays may need to be varied according to the tripping time required and the characteristics of other protection devices used in the network [26]. IDMT Relays are generally classified in accordance with their characteristic curve which would indicate the speed of the operation. These are distinguished by the gradient of their curves. IEC and ANSI ANSI/IEEE Standards define the operating time mathematically by the following expression [15]

$$t = TMS \,.\, \frac{\beta}{PSM^{\alpha} - 1} + L \,, \tag{8}$$

where t = relay operating time in seconds,
TMS = time multiplier setting,
PSM = plug setting multiplier, and
L = constant.

The constants α and β determine the slope of the relay characteristics. The values of α, β, and *L* for various standard overcurrent relay types manufactured under ANSI/IEEE and IEC Standards are given in Table 4. Typical characteristics for both types are shown in Figure 24 and Figure 25.

Table 4: IEEE and IEC constants for standard Overcurrent Relays – ref [15]

Curve description	Standard	α	β	L
Moderately inverse	IEEE	0.02	0.0515	0.114
Very inverse	IEEE	2.0	19.61	0.491
Extremely inverse	IEEE	2.0	28.2	0.1217
Inverse	CO8	2.0	5.95	0.18
Short-time inverse	CO2	0.02	0.0239	0.0169
Standard inverse	IEC	0.02	0.14	0
Very inverse	IEC	1.0	13.5	0
Extremely inverse	IEC	2.0	80.0	0
Long-time inverse	UK	1.0	120	0

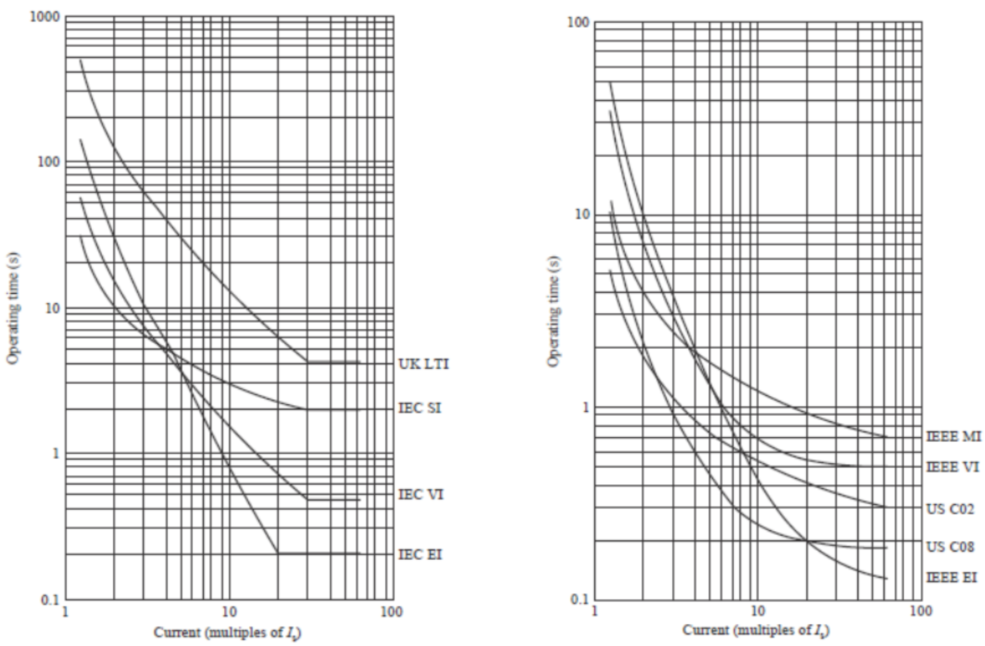
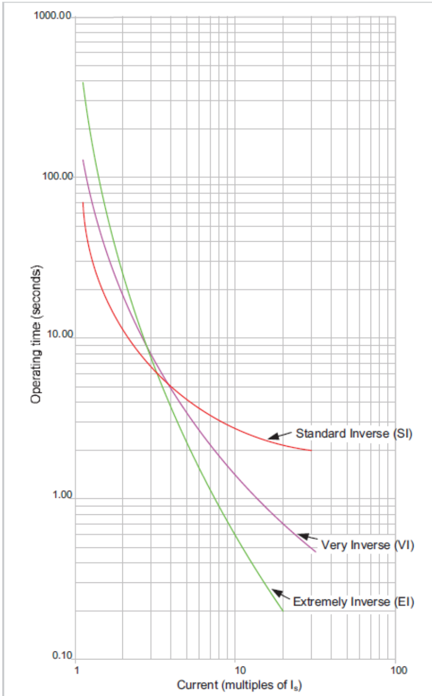


Figure 24: IEC (Left) and ANSI/IEEE (Right) Overcurrent Relays – from ref [15]



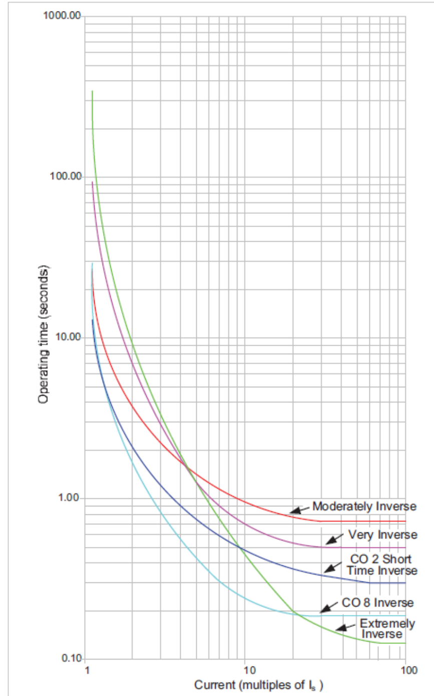


Figure 25: IEC (Left) and North American IDMT Relays (Right) – from ref [26]

3.4 SELECTIVITY & DEVICE COORDINATION

3.4.1 Coordination Background

Isolating an electrical fault condition to the smallest area possible is essential in providing the most reliable electrical distribution system with maximum uptime for your facility. Expensive electronic distribution protection equipment is not worth the extra cost unless a proper protective device coordination study is provided by an experienced electrical engineer [28].

A properly coordinated system will limit an electrical fault to the nearest upstream protective device [28]. Selective coordination generally describes the design of an electrical system in which the upstream protective device (fuse or circuit breaker) nearest to the system fault clears the fault without affecting the protective devices that are upstream from it. Figure 26 illustrates this concept, where a fault is seen on a feeder circuit breaker in a panel. In this example, the fault on the feeder serving panel (M) is protected by circuit breaker (L). With proper action, this will not trip protective devices (G), (E), or (A) upstream — and the fault is contained so that buses (B) and (H) are unaffected, as are the panels marked (N)[30].

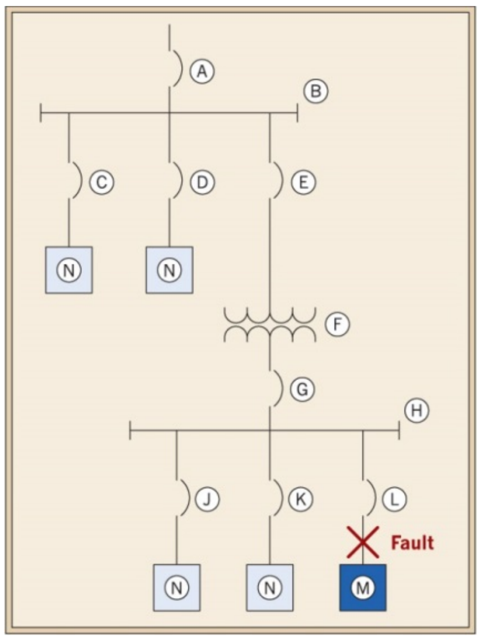


Figure 26: Selectively Coordination in Electrical System – ref [30]

Article 100 of the National Electric Code defines Selective Coordination as follows:

> **"Coordination (Selective):** Localization of an overcurrent condition to restrict outages to the circuit or equipment affected, accomplished by the

selection and installation of overcurrent protective devices and their ratings or settings for the full range of available overcurrents, from overload to the maximum available fault current, and for the full range of overcurrent protective device opening times associated with those overcurrents."

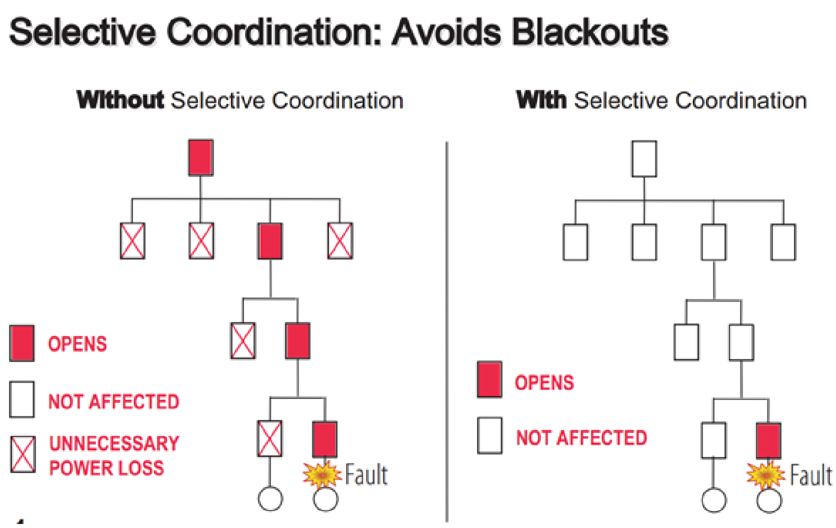


Figure 27: Coordination vs Non-Coordination – from ref [12]

The proper selection and coordination of protective devices is mandated in Article 110.10 of the National Electrical Code:

"110.10 Circuit Impedance, Short-Circuit Current Ratings, and Other Characteristics: The overcurrent protective devices, the total impedance, the equipment short circuit current ratings, and other characteristics of the circuit to be protected shall be selected and coordinated to permit the circuit protective devices used to clear a fault to do so without extensive damage to the electrical equipment of the circuit. This fault shall be

> assumed to be either between two or more of the circuit conductors or between any circuit conductor and the equipment grounding conductor(s) permitted in 250.118. Listed equipment applied in accordance with their listing shall be considered to meet the requirements of this section."

For a protective system, Selectivity is a general term used in describing the interrelated performance of relays and other protective devices, whereby a minimum amount of equipment is removed from service for isolation of a fault or other abnormality. Selectivity is a desirable characteristic in any protection scheme. However, it is not always possible to obtain the desired degree of system and equipment protection in a selective fashion. Usually, an optimum setting is achieved for satisfactory performance [8]. The term Coordination is sometimes used to describe a reasonable compromise, based on an engineering evaluation, between the mutually desirable but competing objectives of maximum system protection and maximum circuit availability. The protective device ratings and settings recommended from a coordination study must be the best balance between these factors [8].

The IEEE Standard 141 - Electrical Power Distribution for Industrial Plants (Red Book) describes the purpose of Electrical Coordination Studies as follows:

> "The primary purpose of a coordination study is to determine satisfactory ratings and settings for the electric system protection devices. The protection devices should be chosen so that pickup currents and operating times are short but sufficient to override system transient overloads such as inrush current experienced when energizing transformers or starting

motors. Further, the devices should be coordinated so that the circuit interrupter closest to the fault opens before other devices.

Determining the ratings and settings for protective devices requires familiarity with NEC requirements for the protection of cables, motors, and transformers, and with ANSI/IEEE C57.12.00-1980 for transformer magnetizing inrush current and transformer thermal and magnetic stress damage limits [32]."

IEEE Standard. 242 - Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (Buff Book) also states that

"The objectives of electrical system protection and coordination are to prevent injury to personnel, to minimize damage to the system components and to limit the extent and duration of service interruption whenever equipment failure, human error or adverse natural events occur in any portion of the system [33]."

Hence, there are three fundamental objectives/aspects to overcurrent protection which engineers should keep in mind while selecting and setting protective devices:

1. *Safety*: Personal safety requirements are met if protective devices are rated to carry and interrupt the maximum available load current as well as withstand the maximum available fault currents. Safety requirements ensure equipment is of

sufficient rating to withstand the maximum available energy of the worst-case scenario [29]. Life safety requirements should never be compromised [31].

2. *Equipment Protection*: Protection requirements are met if overcurrent devices are set above load operation levels and below equipment damage curves [29]. Conductor, cable, transformer and distribution equipment damage information is defined in applicable equipment standards. Capacitor, motor and generator damage information is component specific, and is normally provided by the manufacturer. Based on system operating and equipment sizing practices equipment protection is not always possible [31].

3. *Selectivity*: Selectivity goals are met if in response to a system fault or overload, the minimum area of the distribution system is removed from service. Again, based on system operating and equipment selection practices selectivity is not always possible [31].

Some of the additional key benefits of a Protective Device Coordination Study are:

- Increased facility reliability i.e., minimize system downtime and nuisance device operations
- Increased facility operating efficiency and help prevent downtime
- Prevent damage by identifying underrated equipment
- Prevent damage by identifying overloaded equipment
- Minimize damage to electrical apparatus due to overloads

- Minimize nuisance and false trips of protective devices due to transients, inrush amperage, and starting currents
- Avoid unnecessary blackouts and brownouts to the electrical power system

3.4.2 Data Required for Coordination Study

Short-circuit calculations are a prerequisite for a coordination study. Short-circuit results establish minimum and maximum current levels at which coordination must be achieved and which aid in setting or selecting the devices for adequate protection [56]. The next step in the process is obtaining information about the protective devices. Table 5 presents sample data about fuses, circuit breakers and relays required in a Coordination Study. A complete list can be found in Appendix III – courtesy of BICE Engineering and Consulting.

Table 5: Information for Protective Devices for Coordination Study

Fuses	**Circuit Breakers**	**Relays**
Manufacturer	Manufacturer	Manufacturer
Type	Type	Type
Continuous current rating	Frame size	Ampere tap adjustment range
	Ampere rating or Current sensor rating	Time delay adjustment range
	Long-time adjustment range	Instantaneous adjustment range
	Short-time adjustment range	
	Instantaneous adjustment range	

3.4.3 Computer-Aided Coordination

Overcurrent protection and coordination studies for electrical distribution systems have become much easier to perform with the emergence of several commercially available software programs that run on a personal computer [34]. Examples of such industry approved software programs include ETAP, SKM Power Tools for Windows, EasyPower, EDSA, ASPEN, CYME etc.

Figure 28: Logos of Power Systems Analysis Modeling Software

These computer software programs are utilized to generate the graphical representation of the Time-Current Characteristic (TCC) curves of the protective overcurrent devices under review. To begin, the TCC curves of the protective devices are inserted onto a computer-generated TCC graph consisting of a log-log grid with a time (seconds) vertical axis and a current (amperes) horizontal axis at a given voltage [35]. These programs have built-in libraries of protective device time-current curves, damage curves for cable and transformers, and motor starting curves, thereby facilitating the design of a selectively coordinated protection [34].

The TCC curves for obsolete protective overcurrent device can be manually entered into the computer software's data library, allowing the TCC curve to be used in the current and future studies. The TCC curves for the protective overcurrent devices are shown on the TCC graph, and the curve is extended to the short-circuit fault current that was calculated as part of the short-circuit analysis [35]. The TCC curves for protective overcurrent devices at different voltage levels can also be plotted but are shifted automatically by the computer software by the voltage ratio. In addition, it is quite common that a simplified single-line diagram will be shown on the TCC graph to aid in identifying the portion of the electrical distribution system with which the TCC graph is associated [35].

One of the greatest benefits of using a graphical computer program for coordination and protection is that time-current curves are displayed on the screen and any changes to equipment settings are updated automatically to see how these adjustments affect the time-current curves. This feature enables better "fine-tuning" of protective device settings in order to achieve the best coordination possible while maintaining protection of the distribution system [34]. The protective overcurrent device pickup settings must be evaluated with respect to the protected circuit's ampacity or downstream equipment's continuous current ratings. The fault clearing time of each protective overcurrent device for a fault at a given location must also be evaluated as well. For selective coordination between protective overcurrent devices, a time separation between the protective overcurrent devices' TCC curves must be maintained. Adjustments to the protective overcurrent device settings can be made to properly protect the cable circuits and the electrical equipment, as well as adjusting the time separation between the protective overcurrent devices [35].

We see that Selective protective coordination is more of an art than an exact science. The selection of ratings and settings of overcurrent protective devices to provide system protection and selective operation is often a trial and error process. The electrical engineer must review the electrical distribution system and the associated TCC curves to determine if selective coordination is possible. There will be instances where two overcurrent protective devices are on the same feeder circuit, and therefore selective coordination may not exist. In these instances, the lack of selective coordination will not increase the area of an electrical outage for a fault located on the load side of the feeder circuit and is therefore acceptable [35]. Often, a compromise between protection and coordination must be made and some overlap of characteristics may be necessary for the purposes of protection. Protective Device Settings Guidelines for Selectivity and Equipment Protection is covered in Section 3.4.4.

Steps for Using Computer Software To Achieve A Well-Protected Coordinated Electrical System – list of steps from ref [34]:

1. Draw a one-line diagram for the distribution of the electrical power to the loads.

2. Calculate the maximum available short circuit current at each bus where protective devices are located in the system. Protective devices must have interrupting capacities that exceed the maximum available fault current at that bus.
3. Select as a voltage base the predominant voltage in the electrical system.
4. Start with the largest downstream motor or other end-use load first in sizing overloads and circuit breakers or fuses. Work from the bottom of the one-line diagram upstream just as one would in sizing conductors and transformers.
5. In the software program select either a motor starting curve or a cable or transformer damage curve and display it on the time-current curve chart.
6. Check the software program's library of protective devices for the manufacturer of the upstream protective device that you want to use. If contained in the library, choose it and select the adjustable settings so that the downstream equipment is protected from damage from faults or overloads. If the library does not happen to have the specific manufacturer's device, obtain the manufacturer's time-current curves and add the device to the library.
7. Check if the protective device you have chosen is truly protecting downstream equipment (cable, transformer, motor, etc.) If not, select a different rating of the same type of device.
8. Choose the next in series upstream damage curve and protective device from the library of available cable or transformer damage curves and the protective devices.

9. Coordinate overcurrent protection devices so that the one closest to a fault or overload opens first.
10. "Fine-tune" any adjustable settings or sizes so that devices are selectively coordinated AND all equipment is properly protected.
11. Go to the next largest downstream motor or other endues load and return to step 4 to start a new chart of time-current curves.

Use of the (suggested) steps outlined above in conjunction with one of the commercially available protection and coordination software programs will enable engineers to properly design an electrical distribution system that not only is well-protected but also one that should be relatively free of nuisance trips and limits the amount of equipment affected when a short circuit or overload event does occur. In a Protective Device Coordination Study, the following deliverables are generated:

- *Protective Device Setting Sheets:* These document the ratings and settings of fuses, thermal magnetic circuit breakers, electronic circuit breakers, low-voltage power circuit breaker trip units and protective overcurrent relays. The Protective Device Setting sheets will also indicate changes to the original settings of the protective overcurrent devices [35].
- *Time-Current Curves*: An additional deliverable includes TCC graphs that were generated as part of the protective device coordination study [35].

Due to the life safety, equipment protection and selectivity requirements of electrical system protection design, it is strongly recommended that an experienced professional electrical engineer, familiar with the applicable codes and standards, objectively review the results of the overcurrent coordination study to properly size, select and set the characteristics of protective devices.3.4.4.

3.4.4 Protective Device Setting Guidelines

Overcurrent coordination is generally performed in accordance with the *IEEE Standard 242 - Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems* with protective device settings conforming to the applicable sections of the National Electrical Code [36]. Performing overcurrent coordination studies is a skill required of every electric power system engineer and a background in equipment damage characteristics, along with knowledge of TCC landmarks is necessary to understand the basic principles of equipment protection [31].

A few guidelines for achieving adequate equipment protection and acceptable selectivity are outlined in this section. The material presented in this section is obtained from references [31], [36] and [37].

3.4.4.A TCC Equipment Protection Guidelines

Cable/Feeder Protection Philosophy [31]:

Step 1 – Identify TCC Landmarks

- Ampacity – located in the upper decade
- Intermediate Overload Curve – located in the upper 2 decades (typically not shown)
- Short Circuit Damage Curve – located in the bottom 3 decades

Step 2 – Identify TCC Areas

- Equipment Operating Area – located to the left and below the ampacity
- Equipment Damage Area – located to the right and above the intermediate overload and short circuit damage curves

Step 3 – Size and Set the Protective Device

- Set the protection device pickup at or below the ampacity
- Set the protection device characteristic curve below the intermediate overload and short circuit damage curves

Additional Comments

- If the maximum through-fault current penetrates the limits of the cable short circuit damage curve, insulation damage will occur.
- If the maximum through-fault current penetrates the limits of the conductor short circuit damage curve, conductor damage will occur.
- The through-fault current is defined as the maximum current that can flow for a short circuit located on or beyond the load-side feeder terminals.

Refer to TCC illustration for Cable Protection in Figure 29 below:

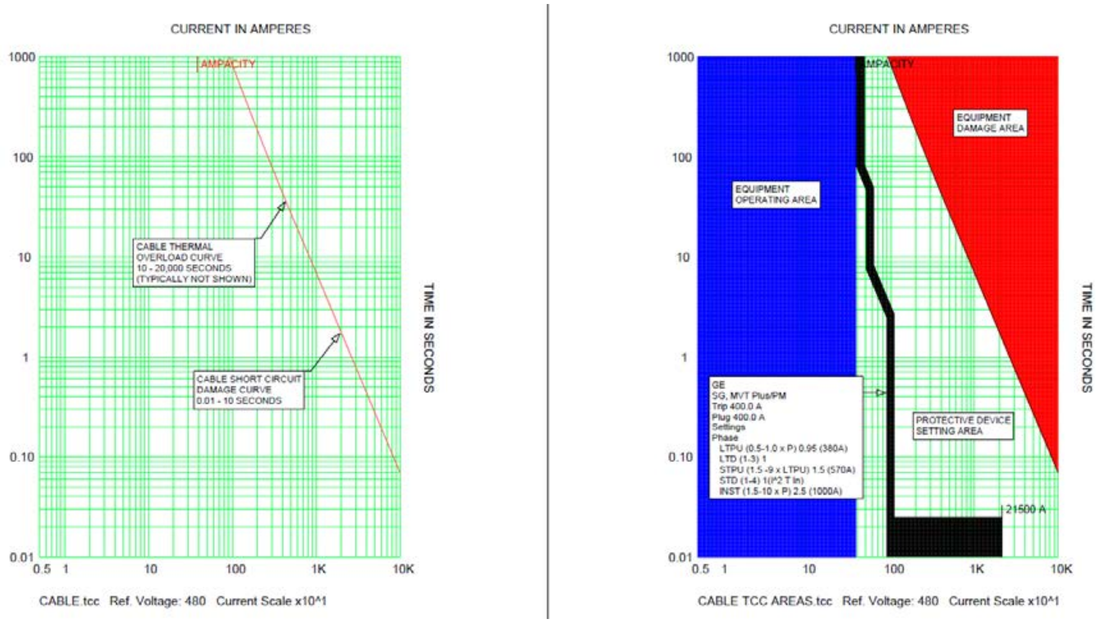


Figure 29: TCC Cable Protection Philosophy – from ref [31]

Transformer Protection Philosophy [31]

Step 1 – Identify TCC Landmarks (all based on the nominal kVA rating)

- Full Load Amps – located in the upper decade
- Thermal Damage Curve – located in the upper 3 decades
- Mechanical Damage Curve – located in the middle decade
- Inrush point defined @ 12 x FLA and 0.1 seconds
- Inrush point defined @ 25 x FLA and 0.01 seconds (Fuse applications only)

Step 2 – Identify TCC Areas

- Equipment Operating Area – located to the left and below the full load amps and inrush points
- Equipment Damage Area – located to the right and above the through-fault damage curves

Step 3 – Size and Set Protective Device

- Set the protection above the full load amps and inrush point(s)

• Set protection below the through-fault damage curves

Additional Comments

• If current penetrates the limits of the thermal damage curve, insulation damage may occur.

• If current penetrates the limits of the mechanical damage curve, cumulative mechanical damage may occur.

NOTE: Transformer overcurrent protective device settings should comply with the requirements of NEC Section 450.3.

Refer to TCC illustration for Transformer Protection in Figure 30 below:

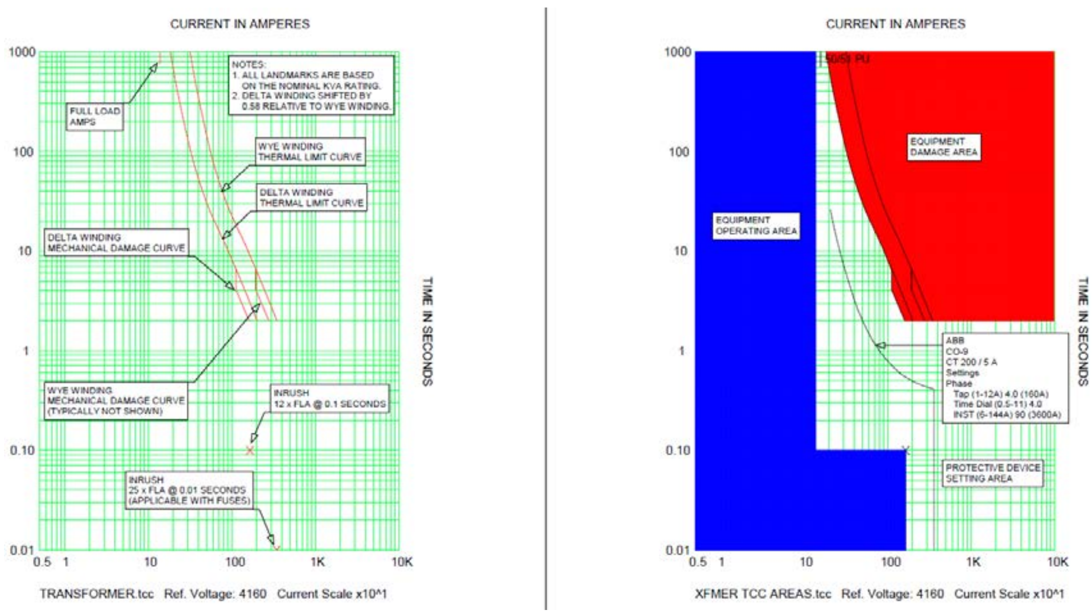


Figure 30: TCC Transformer Protection Philosophy – from ref [31]

Motor Protection Philosophy [31]

Step 1 – Identify TCC Landmarks

• Full Load Amps – located in the upper decade

• Motor Starting Curve – located in all 5 decades

• Rotor Safe Stall Point – located in the upper middle decades (Typical of LV motors)

• Stator Damage Curve – located in the upper decade (Typical of MV motors)

• Rotor Damage Curve – located in the middle decades (Typical of MV motors)

Step 2 – Identify TCC Areas

• Equipment Operating Area – located to the left and below the motor starting curve

• Equipment Damage Area – located to the right and above the safe stall point for LV motors, or the running overload and locked rotor thermal limit curves for MV motors

Step 3 – Size and Set Protective Devices

• Set protection above the full load amps and motor starting curve

• Set protection below the hot stall point for LV motors, or the running overload and locked rotor thermal limit curve for MV motors

Additional Comments

• If a motor operates above the limits of the running overload thermal limit curve, stator insulation life is reduced.

• If a LV motor is allowed to operate at locked rotor for a time above the hot stall point, rotor damage will occur.

• If a MV motor is allowed to operate at locked rotor for a time above the locked rotor thermal limit curve, rotor damage will occur.

Refer to TCC illustrations for Motor Protection in Figure 31 and 32 below:

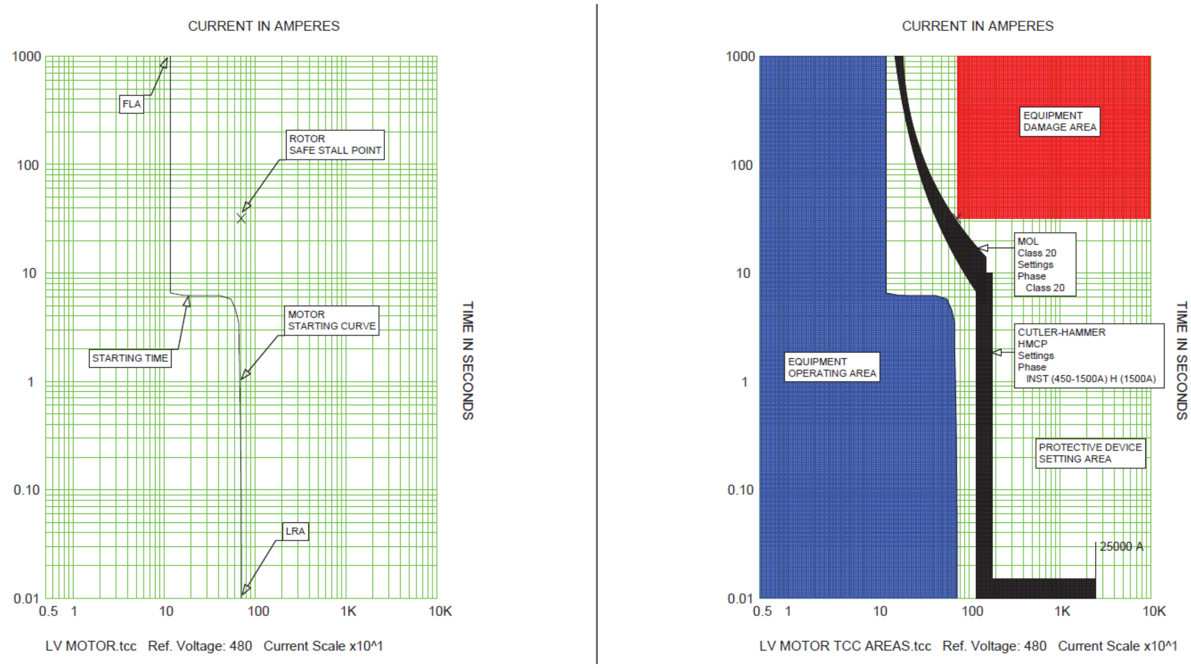


Figure 31: TCC LV Motor Protection Philosophy – from ref [31]

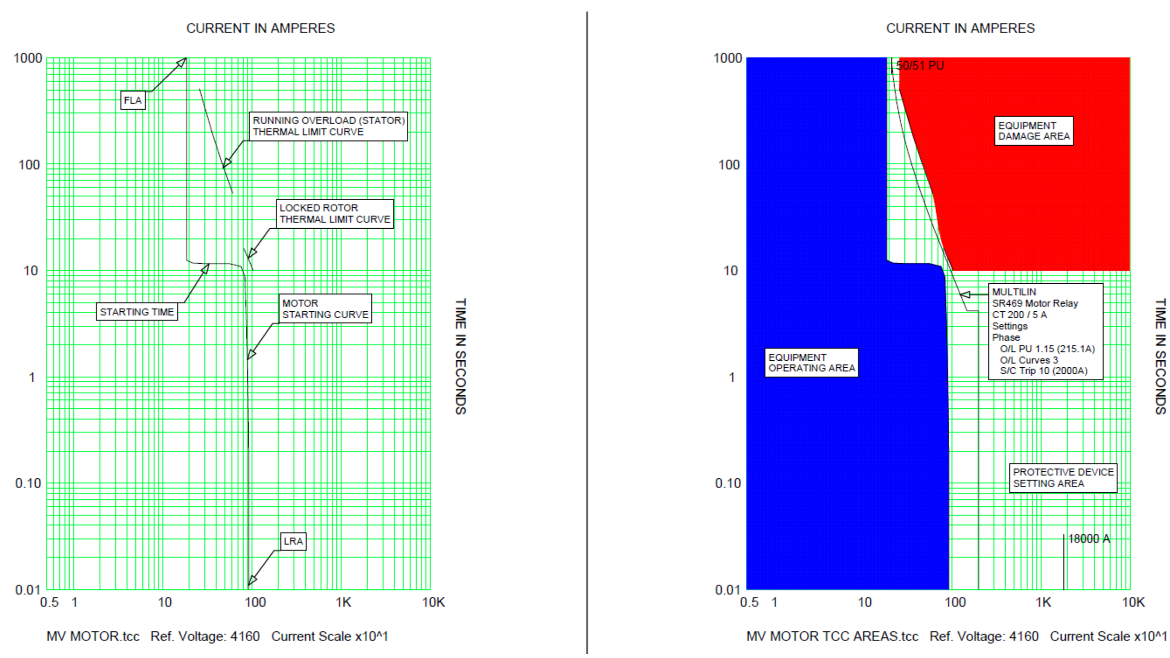


Figure 32: TCC MV Motor Protection Philosophy – from ref [31]

LV Generator Protection Philosophy [31]

Step 1 – Identify TCC Landmarks

- Full Load Amps – located in the upper decade
- Overload Curve – located in the upper 1 or 2 decades
- Decrement Curve – located in the bottom 3 decades

Step 2 – Identify TCC Areas

- Equipment Operating Area – located to the left and below the full load amps and to the left and below the decrement curve in the instantaneous region
- Equipment Damage Area – located to the right and above the overload curve

Step 3 – Size and Set Protection Devices

- Set protection above the full load amps and above the decrement curve in the lowest decade.
- Set protection below the overload curve.
- Set protection to intersect with the decrement curve in the second lowest decade.

Additional Comments

- If current penetrates the limits of the overload curve, stator insulation life is reduced.
- If protection is set above the decrement curve, the device will never trip.

Refer to TCC illustrations for LV Generator Protection in Figure 33 below:

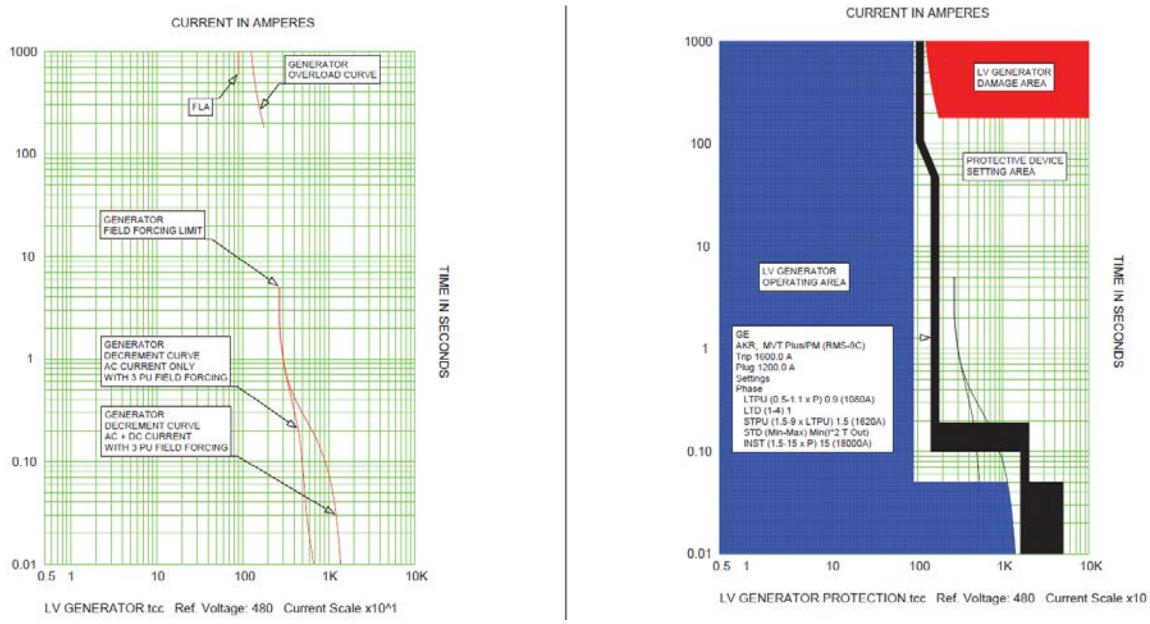


Figure 33: TCC MV LV Generator Protection Philosophy – from ref [31]

3.4.4.B TCC Device Coordination Guidelines

PRINCIPLE OF COORDINATION - TIME AND CURRENT GRADING:

Among the various possible methods used to achieve correct relay coordination are those using either time discrimination or current discrimination, or a combination of both [38].

Current Discrimination:

Current-based discrimination uses the principle that within a power system, the further the fault is from the source, the weaker the fault current is. Current discrimination can be used when there is sufficient difference between the maximum possible operating currents for the primary and backup devices of a pair of devices that need to be coordinated. For example, the setting of instantaneous elements in over-current relays is generally based on current discrimination [38].

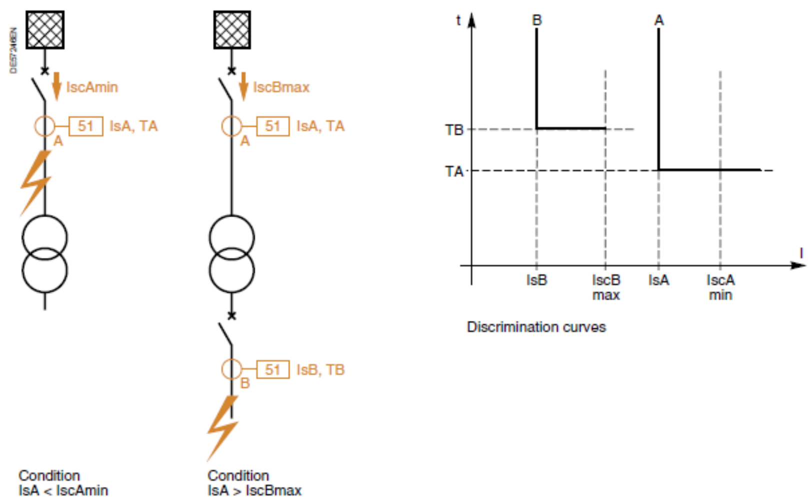


Figure 34: Current-Based Discrimination – from ref [66]

Time Discrimination:

Time-based discrimination consists of assigning different time delays to the overcurrent protection units distributed through the power system. The closer the relay is to the source, the longer the time delay. Time discrimination requires time settings to be selected that will ensure a primary protection device will clear a fault in its protection zone as quickly as possible and that any backup devices will not operate - the primary device successfully clears the fault by normal operation[38].

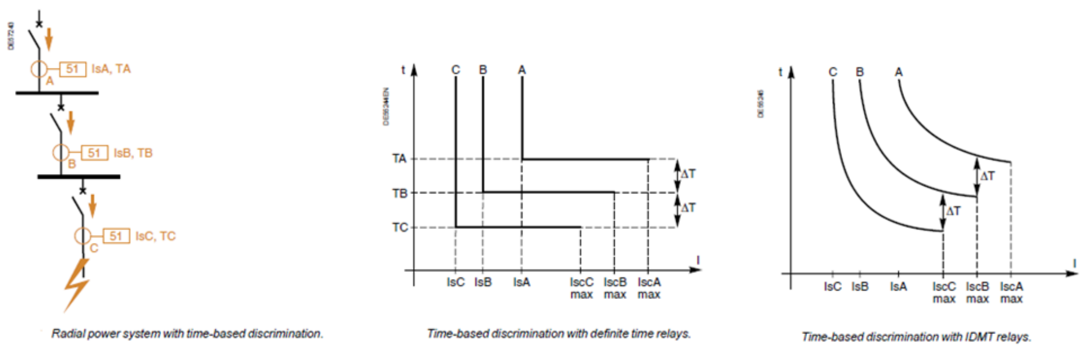


Figure 35: Time-Based Discrimination – from ref [66]

Need for a Discrimination/Coordination Time Interval:

For selective coordination between protective overcurrent devices, a time separation between the protective overcurrent devices' TCC curves must be maintained. The recommended time separation for microprocessor-based and electromechanical overcurrent relays is 0.2 seconds and 0.3 seconds, respectively, plus the circuit breaker operating time. The time separation is required to accommodate CT error, setting errors, tolerances and relay over travel [35] – Refer to Figure 36.

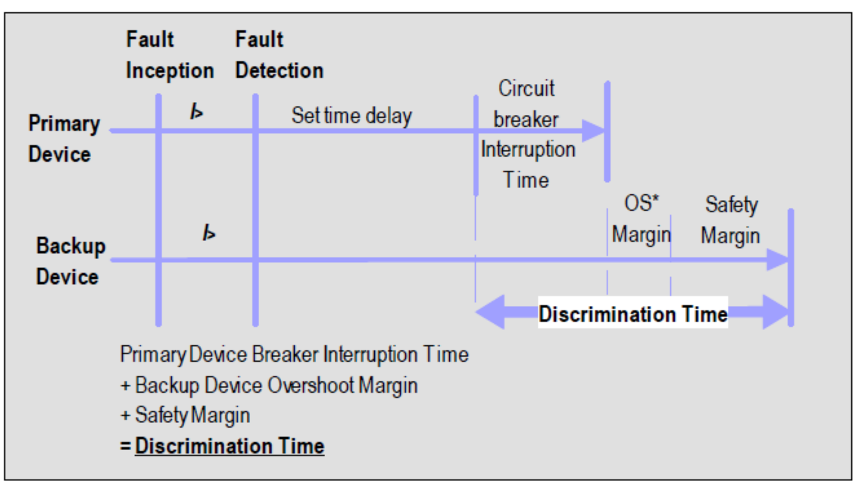


Figure 36: Illustration of Discrimination Time Concept – from ref [38]

The time separation for low-voltage circuit breakers - including thermal magnetic circuit breakers, electronic trip circuit breakers, and low-voltage power circuit breakers - is handled differently than overcurrent relays. The objective with low-voltage circuit breakers is to avoid the crossing of the TCC curves with no intended time delay. The time separation for fuses must be such that the total clearing time of the downstream fuse shall be 75% of the minimum melt curve of the upstream fuse. The time separation for selective coordination of fuses with source side relays/low-voltage circuit breaker is recommended to be 0.2 – 0.3 seconds. The time separation for selective coordination of fuses with load side relays/low-voltage circuit breaker is recommended to be 0.3 seconds [35].

As previously mentioned, overcurrent device settings are chosen to provide an acceptable compromise between sensitivity and selectivity in overcurrent protection. Reference [36] provides the following minimum recommended margins between device characteristics to achieve selective coordination:

1. *Relay - Relay* coordination requires (i) that there be a minimum of 0.25 to 0.40 seconds time margin between the relay curves at the maximum fault current to account for the interrupting time of the circuit breaker, relay over-travel time, relay tolerances, and a safety factor or (ii) that the downline relay curve be less than 90% of the upline relay curve.

   For induction disk relays, the minimum desired time margin for a 5 cycle breaker is generally 0.30 seconds:

5 cycle breaker	0.08 seconds
relay over-travel	0.10 seconds
CT ratio & safety factor	0.12 seconds
	0.30 seconds

For digital relays, the minimum desired time margin for a 5 cycle breaker is generally 0.25 seconds:

5 cycle breaker	0.08 seconds
relay accuracy ±.02 sec.	0.04 seconds
CT ratio & safety factor	0.13 seconds
	0.25 seconds

Margin between pickup levels of ≥ 10% for two devices in series.

2. *Electromechanical Relay - Fuse Coordination* requires a minimum 0.22 second time margin between the curves.
3. Electromechanical *Relay - Low Voltage Breaker Coordination* requires a minimum 0.22 second time margin between the curves.
4. *Static Relay - Fuse Coordination* requires a minimum 0.12 second time margin between the curves.
5. *Static Relay - Low Voltage Breaker Coordination* requires a minimum 0.12 second time margin between the curves.
6. *Fuse - Fuse Coordination* requires that the total clearing time of the downline fuse curve be less than 75% of the minimum melt time of the upline fuse curve to account for pre-loading (also refer to Section 3.3.1.D).

7. *Fuse - Low Voltage Breaker Coordination* requires that the down-line breaker maximum time curve be less than 75% of the minimum melt time of the up-line fuse curve to account for pre-loading.
8. *Fuse - Relay Coordination* requires a minimum 0.3 second time margin between the curves.
9. *Low Voltage Breaker - Fuse Coordination* requires a minimum 0.1 second time margin between the curves to allow for temperature variations in the fuse.
10. *Low Voltage Breaker - Low Voltage Breaker Coordination* requires only that the plotted curves do not intersect since all tolerances and operating times are included in the published characteristics.
11. *Low Voltage Breaker - Relay Coordination* requires a minimum 0.2 second time margin between the curves.

Refer to Figures 37 through 41 for TCC illustrations on the application of Coordination Time Intervals.

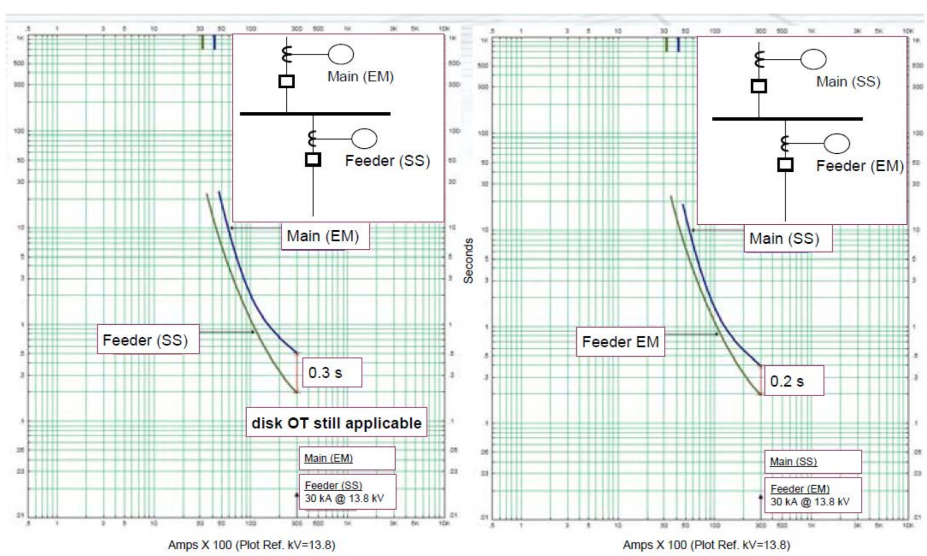


Figure 37: TCC Illustration Relay-Relay Coordination – from ref [67]

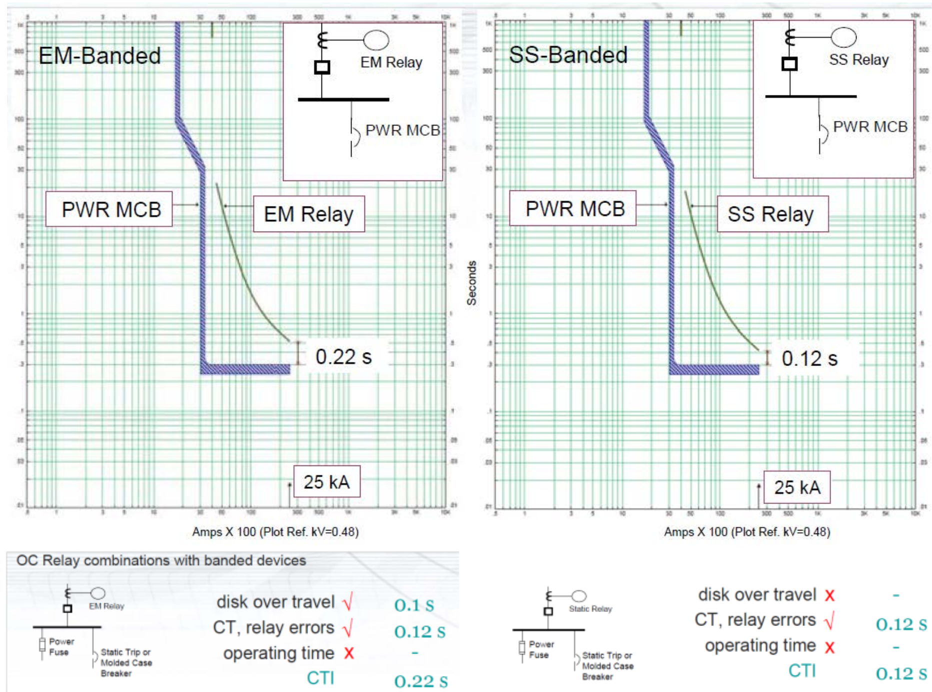


Figure 38: TCC Illustration Relay-Breaker Coordination – from ref [67]

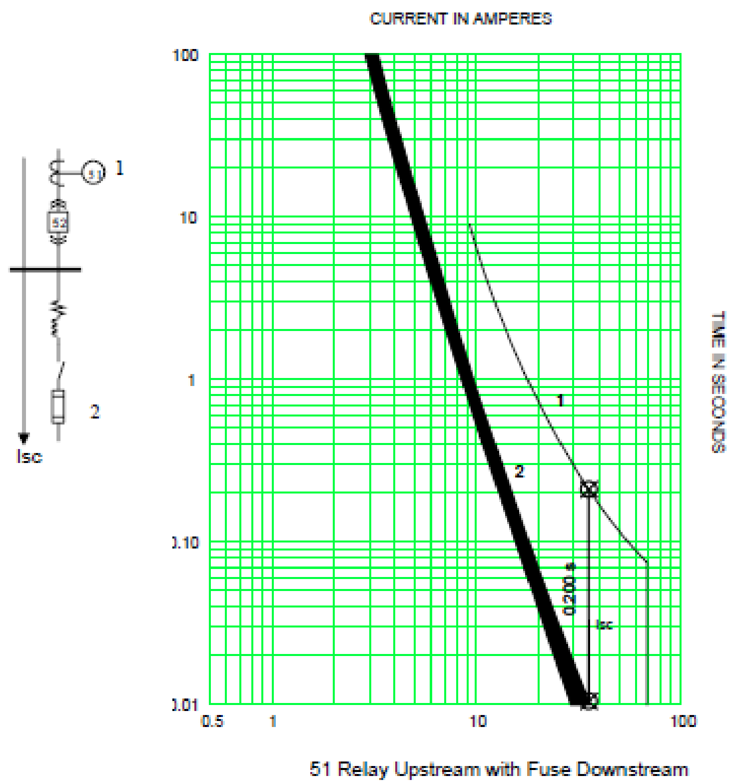


Figure 39: TCC Illustration Relay-Fuse Coordination – from ref [31]

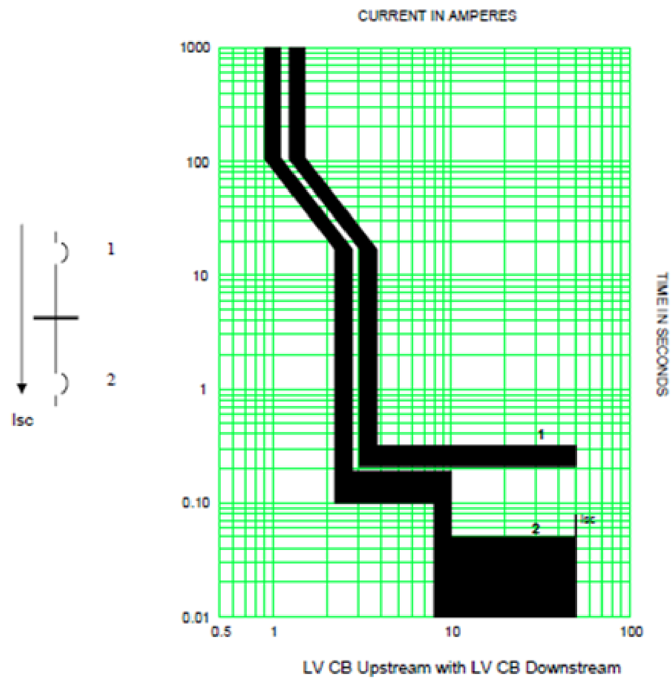


Figure 40: TCC Illustration Breaker-Breaker Coordination – from ref [31]

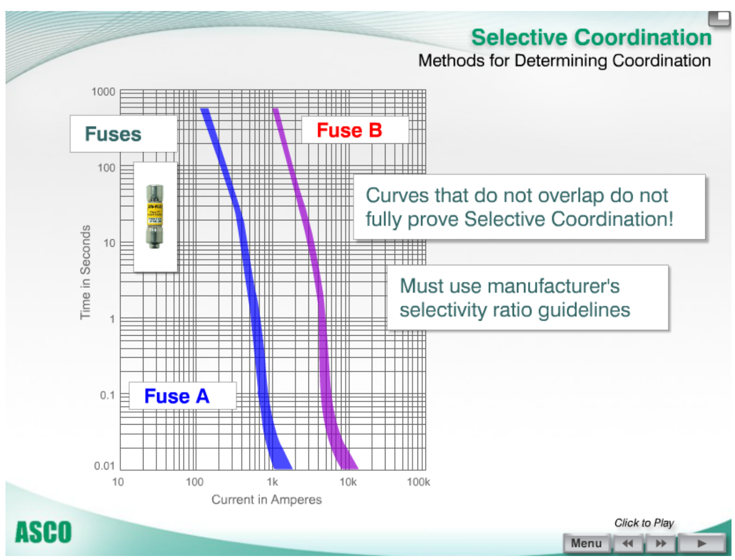


Figure 41: TCC Illustration Fuse-Fuse Coordination – from ASCO Power

CHAPTER 4 ARC FLASH STUDIES AND ANALYSIS

4.1 ARC FLASH: BACKGROUND & INTRODUCTION

Multiple arc flash incidents occur in workplaces across the U.S. every month. To be factual, five to ten arc explosions occur in electric equipment every day in the United States, according to statistics compiled by CapSchell, Inc., a Chicago based research and consulting firm that specializes in preventing workplace injuries and deaths [57].

The idea of arc flash has been around since Thomas Edison invented electricity in the 1870s. Arc flash hazard was initially publicized in 1982 in Ralph Lee's paper titled *"The Other Electrical Hazard: Electric Arc Blast Burns."* Lee was a pioneer in electrical safety. As the collateral damage it caused became increasingly evident, the US Occupational Safety and Health Administration (OSHA) developed regulations governing this issue. OSHA holds employers responsible for worker and workplace safety. It states that "*each employer shall furnish to each of his employees' employment and a place of employment which are free from recognized hazards that are causing, or are likely to cause, death or serious physical harm to employee*." [40].

Then Electric Power Research Institute estimates direct and indirect costs to an employer from a fatal electrical accident in the millions. This includes: medical costs, lost productivity, workers compensation, hiring and re-training, equipment replacement, facility repair, insurance premium increases, OSHA citations, litigation and punitive damages, etc.; and in the end, OSHA will enforce compliance, including performing an arc flash hazard analysis, through a succession of inspections [39].

In 1995, the Department of Energy (DOE) named the National Fire Protection Association (NFPA) 70E as the basis document for electrical safety in all facilities. This was the first document of formal arc flash regulation, which incorporated the idea of an "*arc flash boundary*" based on Ralph Lee's paper [40]. Since then, there have been changing guidelines and regulations aimed at reducing the number of Arc Flash related injuries and deaths have focused attention on the dangers of Arc Flash events in energized low and medium voltage electrical equipment. While every facility will have its own unique set of challenges, routine inspections, maintenance testing and associated costs, it has been proven, without exception, it is far more expensive to allow one arc flash accident to occur than to prevent it [39].

Chapter 4 provides an overview of arc flash hazards, regulatory issues, and methods to apply the standards available to determine conditions and procedures required to work safely.

4.2 ARC FLASH DANGERS

4.2.1 What is an Arc Flash Hazard?

Arc Flash Hazard as per reference [41] is defined as: "A dangerous condition associated with the release of energy by an electric arc".

Broken down to its components, we get:

Arc: current flowing through air,

Flash: release of energy including a bright flash of light; and,

Hazard: the danger posed to personnel in the vicinity of the arc [42].

4.2.2 Origin of Arc Flash Hazards

Before we discuss arc flash incidents themselves, we need to understand the cause. The most alarming fact is that arc flash incidents occur when electrical systems are energized. The basic rule is to de-energize electrical equipment, or place it in an electrically safe working condition, prior to servicing or maintenance. OSHA regulations state in 1910.333 (a) that workers should not work on live equipment (greater than 50 Volts) except for one of two reasons: (i) De-energizing introduces additional or increased hazards such as cutting ventilation to a hazardous location; and (ii) De-energizing is infeasible due to equipment design or operational limitations such as when voltage testing is required for diagnostics.

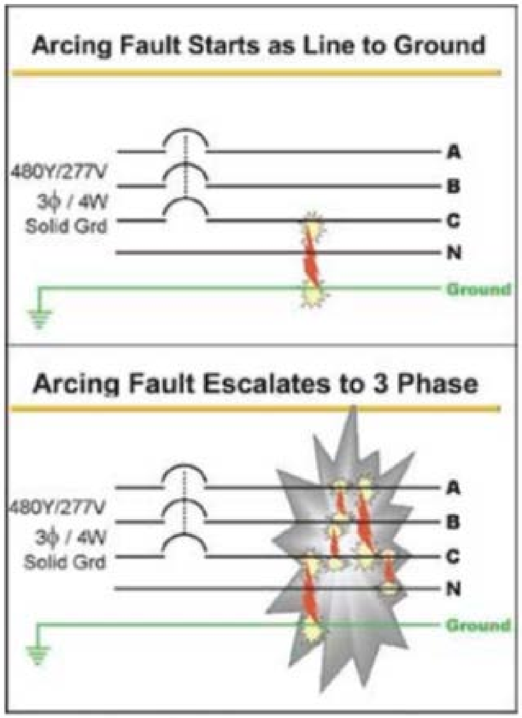
Even though ignoring these regulations and practices is a violation of federal law, the unfortunate fact is that work is often conducted on energized equipment, inviting an electrical injury to occur [43]. When it is necessary to work on energized equipment, you must follow safe work practices including assessing the risks, wearing proper Personal Protective Equipment (PPE), and using the proper tools [44]. More details about PPE is discussed in section 4.4.2.

Arcing Faults

Arc flash incidents are caused by arcing faults. Faults on an electrical system cause current to travel out of its normal path. There are primarily two types of faults: bolted faults and arcing faults. Bolted faults are characterized by a solidly connected fault path causing high levels of current to flow through this solid connection. This type of fault is commonly used when testing electrical equipment for short-circuit current ratings and overcurrent protective devices for interrupting ratings. Arcing faults differ in the fact that the current actually flows through ionized air causing an arc. The major difference between these two types of faults is that the energy in a bolted fault condition is dissipated in the faulted equipment while an arcing fault releases energy out into the surrounding environment [43].

Unlike bolted faults, the predictability of an arcing fault and the energy released vary. This is due to the arcing fault's dependence on many variables. Some of the variables that affect the outcome include

- available bolted short-circuit current on the system,
- the time the fault is permitted to flow (speed of the overcurrent protective device),
- arc gap spacing,
- size of the enclosure or no enclosure,
- power factor of fault,
- system voltage,
- whether an arcing fault can sustain itself, and
- type of system grounding and bonding scheme.



. One major characteristic surrounding arcing faults is progression of the fault to other energized parts of the system caused by the buildup of ionized matter in the arc

Figure 42: Origin & Buildup of Arcing Fault – from ref [43]

One major characteristic surrounding arcing faults is progression of the fault to other energized parts of the system caused by the buildup of ionized matter in the arc [43]. For example, a line-to-ground arcing fault can quickly escalate into a three-phase arcing fault as the ionized gas produced envelops the other energized parts of the equipment. This causes other phases of the electrical system to become involved in the arcing fault, thus increasing the amount of electrical energy feeding into the fault; and increases the extent of the fault and incident. This characteristic is a major driver behind arc flash incidents [43].

To understand this principle of fault progression, look at the physics surrounding an electrical arc. The arc model shown in Figure 43 and Figure 44 shows the physical aspects of an electrical arc.

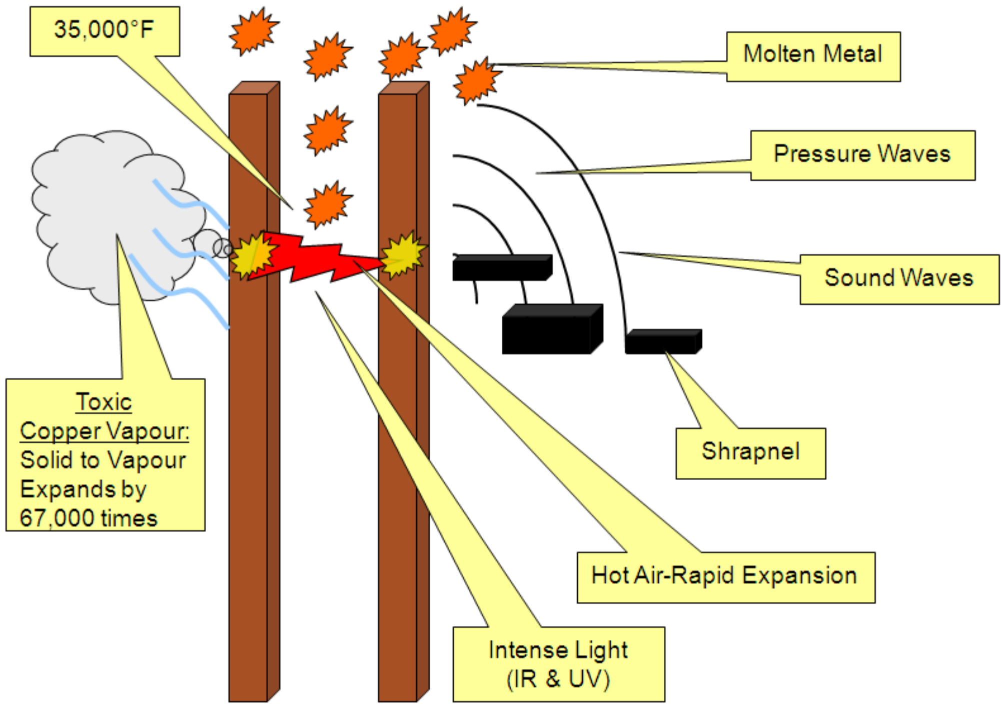


Figure 43: Physical Aspects of an electric Arc – I – from ref [45]

The terminal of the arc is extremely hot having a temperature estimated to be in excess of 35,000°F, roughly four times the temperature of the surface of the sun. An arcing fault usually occurs between phase bus bars, or from phase to neutral or ground. When an arc flash occurs, large amounts of energy can be dissipated in a very short time. This energy causes the ionization and vaporization of the conductive metal materials (highly conductive plasma) and heating of the ambient air creates a rapid volumetric expansion, known as arc blast, and consequently an explosion [45].

During this event, current is conducted through the plasma and the major factor that affects the current magnitude is the impedance of the arc. Intense light, sound waves, shrapnel and molten metal, toxic gases and smoke are also components of the arc flash as indicated in Figures 43 and 44.

The duration and current magnitude of an arcing fault can vary widely. An arc can be initiated by a flashover due to a failure such as breakdown in insulation or by the introduction of a conducting object that accidentally bridges the insulation. Under certain conditions that sustain the arc, arcing faults develop into dangerous arc flash incidents [45].

An Arc Flash therefore is a rapid release of energy due to an arcing fault between a phase conductor and another phase conductor, a neutral conductor or a ground [46]. This results in

- the rapid release of energy which creates an explosion,
- the rapid release of heat due to high temperatures of 35000^{o}F,
- blinding light caused by flash,
- shock/pressure waves,
- sound waves which can damage the ears possibly causing acoustic wave trauma,
- sudden spray of molten metal droplets, and
- Hot shrapnel flying in all directions.

4.2.3 What Causes Electrical Arcing?

As explained above, an arc occurs when electric current flows between two or more separated energized conducting surfaces. Some arcs are caused by human error while a person is working on an energized electrical system; this could be accidental dropping of tools, accidental touching, and improper work procedures [44]. Mechanical failures like loose connections or falling parts can cause electrical arcing. It is not uncommon for a piece of hardware, such as a nut or washer, to fall into energized parts when a door is opened or closed, or when the handle is operated on a switch or circuit breaker [43].

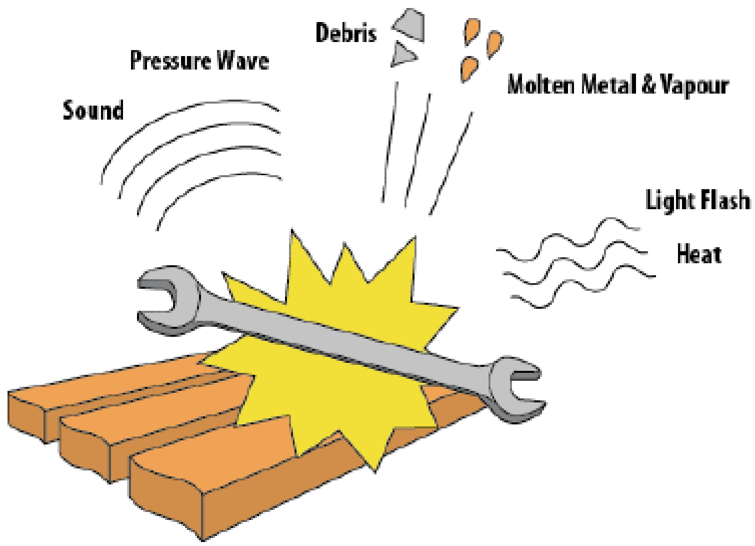


Figure 44: Physical Aspects of an electric Arc – II – from ref [42]

Another common cause of an arc is insulation failure. Build-up of dust, condensation, contamination, and corrosion on insulating surfaces can provide a path for current flow. Spark discharge created during racking of breakers, replacement of fuses, and closing into faulted lines can also produce an arc. Animals like birds, rodents, squirrels, lizards, snakes, etc., can inadvertently bridge the space between conductors or cause leads to slap together, creating an arcing fault [44].

4.2.4 Consequences & Effects of Electrical Arcing

Electrical hazards, such as arc flash, can be extremely damaging to equipment and, more importantly, to people. Exposure to an arc flash frequently results in a variety of serious injuries and in some cases death. Workers have been injured even though they were 10 feet or more away from the arc center [44]. The pressure wave can also knock away personnel away from the heat source; and sometimes from a ladder [43]. As previously mentioned, this pressure blast wave propels molten metal droplets which are hot enough to ignite clothing. In addition, worker injuries can include permanent loss of hearing due to the sound wave, loss of eyesight due to blinding flash light, and severe burns requiring years of skin grafting and rehabilitation. The radiation from arc heating quickly melts and evaporates metal. Consequently, equipment and building structures can be destroyed causing lengthy downtime which require expensive replacement and repair. The cost of treatment for the injured worker can exceed $1,000,000/case. This does not include very significant litigation fees, insurance increases, fines, accident investigation and cost of lost production [44].

An alarming number of electrically related accidents occur each year, often resulting in serious third degree burns or death. In order to relate the level of danger involved, we must investigate some important thresholds for the human body. One important danger associated with arc flash is burns resulting from the high levels of heat. Burns are often categorized as to the extent of the burn. For reference, a second-degree burn threshold, or a "just curable burn threshold," is skin temperature raised to 175°F for 0.1 second, while a third-degree burn threshold or "incurable burn threshold" would result from skin temperature raised to 200°F for 0.1 second. Another important danger would be injury resulting from the intense pressure associated with an arc flash incident [43]. Two important thresholds relating to pressure for the human body include:

- Eardrums: 720 lbs/ft^2
- Lung Damage: 1728 to 2160 lbs/ft^2

The eardrums represent the lower level threshold for damage due to their direct exposure to pressure waves, while lung damage is a good upper threshold due to the protection provided by the rib cage. Extensive tests and analyses by industry have shown that the energy released during an arcing fault is related to two characteristics; (i) the duration of the arcing fault and (ii) the amount of fault current or energy feeding the fault [43]. The calculation of this energy (known as 'incident energy' - details in section 4.6) takes a lot of factors into account. The most important ones are

- Distance - being further away from the arc reduces the hazard,
- Arcing current - a lower current reduces the hazard, and
- Time - a shorter arcing duration reduces the hazard [42].

Distance and arcing current depend on the type of equipment and the power system configuration. Usually it is not easy to change them. Selection and performance of overcurrent protective devices play a significant role in electrical safety. The time it will take to interrupt the arcing current is determined by the delay of the feeding fuse or circuit breaker. Overcurrent protective devices contribute to (i) control the duration of the fault and (ii) sometimes limit the amount of arcing fault current depending on the type of overcurrent protective device selected. The poor electrical conductance of air means that the arcing current is less than the short-circuit current; sometimes only 35% of it – and the actual delay is not immediately obvious. For example, a fuse chosen for its quick operation under short-circuit fault conditions may take up to one second to interrupt the arc. Similarly the magnetic trip on a circuit breaker may not function, leaving the thermal element to interrupt the arc after a much longer delay [42]. Therefore devices that can react quickly to an arcing fault and reduce the amount of fault current available, aid in reducing the energy released. The lower the energy released the better for both worker safety and equipment protection [43].

4.3 ARC FLASH STANDARDS

4.3.1 What Standards Regulate Arc Flash Hazards?

The two driving regulatory bodies related to Arc Flash are the Occupational Safety and Health Administration (OSHA) and the National Fire Protection Association (NFPA) [48]. IEEE Standard 1584 Guide for Performing Arc Flash Hazard Calculations provides techniques for determining arc flash hazard levels - calculating the incident energy to define the safe working distance and aid in selection of overcurrent protective devices and PPE [44].

The NFPA is an international nonprofit organization based in the US that provides codes and standards aimed at reducing fire and other hazards. One of the standards published by the NFPA is the NFPA Standard 70E: Standard for Electrical Safety in the Workplace [42]. It provides guidance on implementing appropriate work practices that are required to safeguard workers from injury while working on or near exposed electrical conductors or circuit parts that are or become energized. NFPA 70E covers electrical hazards including arc flash and helps comply with US work safety regulations.

OSHA is an enforcer of safety practices in the workplace. Though OSHA does not enforce the NFPA 70E standard, the organization does recognize it as industry practice and the administration's field inspectors carry a copy of NFPA 70E for use in addressing safety procedures related to arc flash. Electrical inspectors across the country also enforce the new labeling requirements set forth in the National Electrical Code (NEC) [44].

The NEC included a Section 110.16 requiring the labeling of panels with an arc flash warning beginning with the 2002 edition. The 2015 edition of the NEC made minor changes to the 2011 revision and now reads [47]:

"110.16 Arc Flash Hazard Warning

Electrical equipment, such as switchboards, switchgear, panelboards, industrial control panels, meter socket enclosures, and motor control centers, that are in other than dwelling units, and are likely to require examination, adjustment, servicing, or maintenance while energized, shall be field or factory marked to warn qualified persons of potential electric arc flash hazards. The marking shall meet the requirements in 110.21(B) and shall be located so as to be clearly visible to qualified persons before examination, adjustment, servicing, or maintenance of the equipment."

OSHA regulations that apply to arc flash hazards are in 29CFR 1910 Subparts I, and S. These can be broken down into three general areas, hazard identification and PPE selection, training, and proficiency.

Here are excerpts from 29 CFR:

“1910.132(d) Hazard assessment and equipment selection.

1910.132(d)(1) The employer shall assess the workplace to determine if hazards are present, or are likely to be present, which necessitate the use of personal protective equipment (PPE). If such hazards are present, or likely to be present, the employer shall:

- 1910.132(d) (1) (i) - Select, and have each affected employee use, the types of PPE that will protect the affected employee from the hazards identified in the hazard assessment;
- 1910.132(d) (1) (ii) - Communicate selection decisions to each affected employee; and,
- 1910.132(d) (1) (iii) - Select PPE that properly fits each affected employee. Note: Non-mandatory Appendix B contains an example of procedures that would comply with the requirement for a hazard assessment.
- 1910.132(d) (2) - The employer shall verify that the required workplace hazard assessment has been performed through a written certification that identifies the workplace evaluated; the person certifying that the evaluation has been performed; the date(s) of the hazard assessment; and, which identifies the document as a certification of hazard assessment.

1910.335(a) (1) (i) Personal Protective Equipment

Employees working in areas where there are potential electrical hazards shall be provided with, and shall use, electrical protective equipment that is appropriate for the specific parts of the body to be protected and for the work to be performed.

1910.132(f) Training.

1910.132(f)(1) The employer shall provide training to each employee who is required by this section to use PPE. Each such employee shall be trained to know at least the following:

- 1910.132(f)(1) (i) When PPE is necessary;
- 1910.132(f)(1) (ii) What PPE is necessary;
- 1910.132(f)(1) (iii) How to properly don, doff, adjust, and wear PPE;
- 1910.132(f)(1) (iv) The limitations of the PPE; and,
- 1910.132(f)(1) (v) The proper care, maintenance, useful life and disposal of the PPE.

1910.132(f)(2) Each affected employee shall demonstrate an understanding of the training specified in paragraph (f) (1) of this section, and the ability to use PPE properly, before being allowed to perform work requiring the use of PPE.

1910.132(f)(3) When the employer has reason to believe that any affected employee who has already been trained does not have the understanding and skill required by paragraph (f) (2) of this section, the employer shall retrain each such employee. Circumstances where retraining is required include, but are not limited to, situations where:

- 1910.132(f)(3)(i) Changes in the workplace render previous training obsolete; or
- 1910.132(f)(3)(ii) Changes in the types of PPE to be used render previous training obsolete; or
- 1910.132(f)(3)(iiii) Inadequacies in an affected employee's knowledge or use of assigned PPE indicate that the employee has not retained the requisite understanding or skill."

4.4 LIMITS OF APPROACH & PERSONAL PROTECTIVE EQUIPMENT

4.4.1 Working Distance and Limits of Approach

The picture in Figure 45 shows two distances that are used in an arc flash hazard analysis: the working distance and the arc flash boundary.

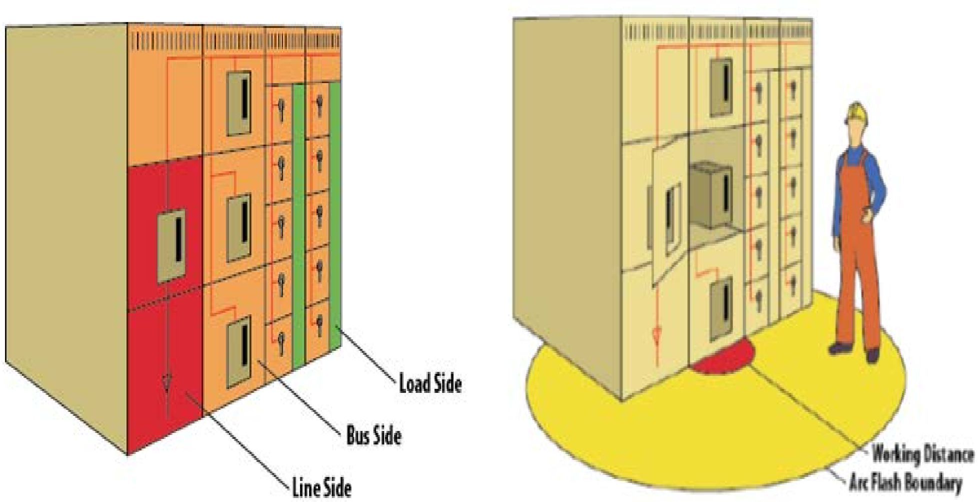


Figure 45: Personnel within Arc Flash boundary – from ref [42]

The working distance is the minimum distance at which a worker is expected to be when an arc flash occurs. It is a fixed number based on the voltage and type of equipment. Since the radiated energy decreases with distance, it will always be maximal at the working distance. Therefore, incident energy is calculated at this point [42].

Moving further away, energy decreases until at some point to the minimum value of 1.2 Cal/cm^2 is reached - this is the Arc Flash Boundary. At this point is defined as an approach limit at a distance from a prospective arc source within which a person could receive a second degree burn if an electrical arc flash were to occur. Outside of this boundary no hazard mitigation is necessary. In Figure 45 above, the worker is standing within the flash protection boundary but not quite at the working distance. In this case personal protective equipment (PPE) is required to protect against the worst case incident energy (calculated at the working distance) [42].

Typical working distance is the sum of the distance between the worker and the front of the equipment and the distance from the front of the equipment to the potential arc source inside the equipment. Table 6, obtained from reference [41]; Informative Annex D Table D.4.3, provides information about typical working distances dependent on the type of equipment.

Table 6: Typical Working Distances – from ref [41]

Classes of Equipment	Typical Working Distance* (mm)
15-kV switchgear	910
5-kV switchgear	910
Low-voltage switchgear	610
Low-voltage MCCs and panelboards	455
Cable	455
Other	To be determined in field

* Typical working distance is the sum of the distance between the worker and the front of the equipment and the distance from the front of the equipment to the potential arc source inside the equipment.

Approach Boundaries:

NFPA 70E defines boundaries that correlate PPE with the type of work being performed [46]. In addition to flash protection, NFPA 70E also defines requirements for shock protection and safe distances for qualified and unqualified personnel [48]. NFPA 70E recommends the identification of two boundaries to define the safe working limits for personnel working in an area with shock hazards. Each area is associated with a level of training and PPE. Figure 45 [41] and Figure 47 illustrate these boundaries – the limited approach boundary, and the restricted approach boundary.

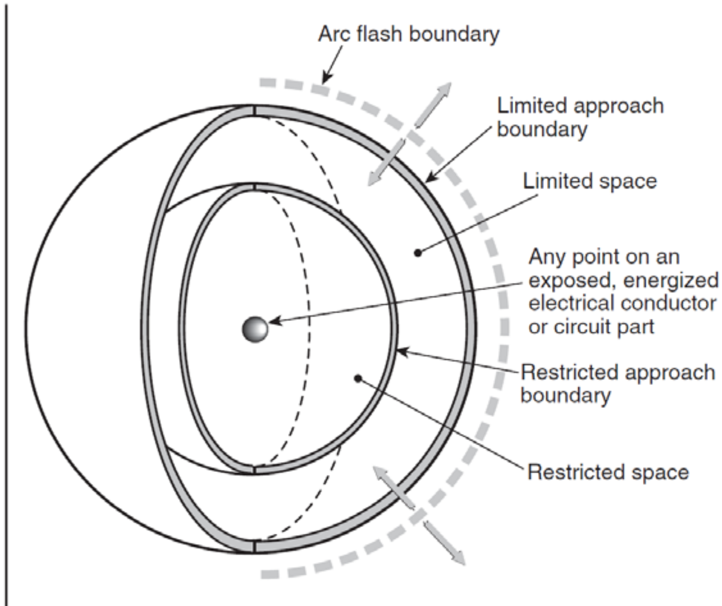


Figure C.1.2.3 Limits of Approach.

Figure 46: Limits of Approach – I – from ref [41]

Limited Approach Boundary:

Reference [41] defines the Limited Approach Boundary as an approach limit at a distance from an exposed energized electrical conductor or circuit part within which a shock hazard exists.

Restricted Approach Boundary:

Reference [41] defines the Restricted Approach Boundary as an approach limit at a distance from an exposed energized electrical conductor or circuit part within which there is an increased likelihood of electric shock, due to electrical arc-over combined with inadvertent movement, for personnel working in close proximity to the energized electrical conductor or circuit part.

Arc Flash Boundary:

When an arc flash hazard exists, an approach limit at a distance from a prospective arc source within which a person could receive a second degree burn if an electrical arc flash were to occur. A second degree burn is possible by an exposure of unprotected skin to an electric arc flash above the incident energy level of 5 J/cm^2 (1.2 Cal/cm^2). [41]

The Limited and Restricted Boundaries are based on the nominal voltage of the energized equipment. This is specified in NFPA 70E – Table 130.4 (D) (a) [41].

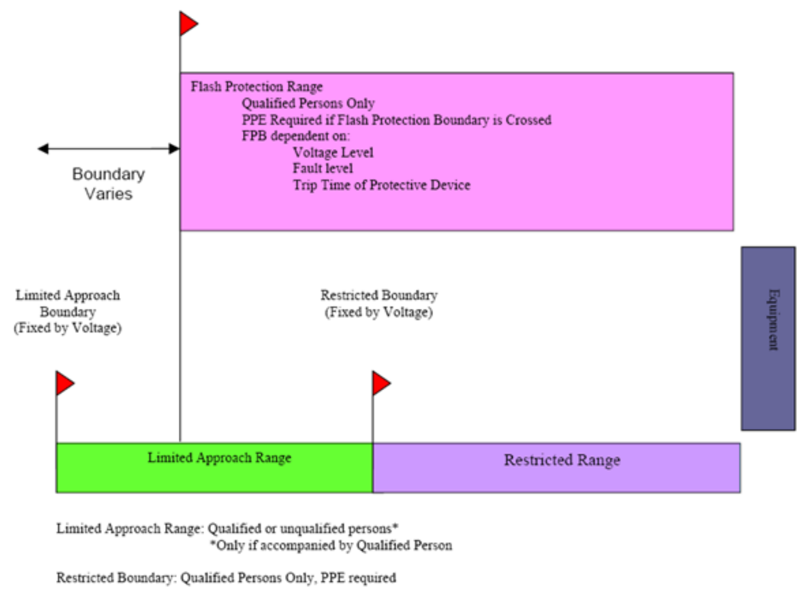


Figure 47: Limits of Approach – II

The Arc Flash Boundary is independent of the shock boundaries. This boundary is calculated based on several factors such as voltage, available fault current, and time for the protective device to operate and clear the fault. The flash protection boundary for an electrical system is determined using the calculating methods contained in NFPA 70E and IEEE Standard 1584.

What is the definition of a Qualified Person?

One who has demonstrated skills and knowledge related to the construction and operation of electrical equipment and installations and has received safety training to identify and avoid the hazards involved.

NOTE: Unqualified Person - A person who is not a qualified person. Unqualified persons shall be trained in, and be familiar with, any electrical safety-related practices necessary for their safety [41].

4.4.2 Personal Protective Equipment (PPE)

How do you determine what PPE is required?

In order to select the proper PPE, incident energy must be known at every location where workers may be required to perform work on energized equipment. These calculations need to be performed by a qualified person such as an electrical engineer. All parts of the body that may be exposed to the arc flash need to be covered by the appropriate type and quality of PPE. Proper PPE can include arc-rated clothing, hard hat, face shield, safety glasses, gloves, shoes, and more depending upon the magnitude of the arc energy [44]. The use of PPE by qualified personnel is mandated by NFPA Standard 70E. The following passages from the standard explain a few reasons for appropriate PPE:

NFPA 70E Section 130.7(A) Employees working in areas where electrical hazards are present shall be provided with, and shall use, protective equipment that is designed and constructed for the specific part of the body to be protected and for the work to be performed.

NFPA 70E Section 130.7(C)(1) When an employee is working within the restricted approach boundary, the worker shall wear PPE in accordance with 130.4. When an employee is working within the arc flash boundary, he or she shall wear protective clothing and other PPE in accordance with 130.5. All parts of the body inside the arc flash boundary shall be protected.

NFPA 70E Section 130.7 (16) Protective Clothing and Personal Protective Equipment (PPE). Once the arc flash PPE category has been identified from Table 130.7(C)(15)(A)(b) or Table 130.7(C)(15)(B), Table 130.7(C)(16) shall be used to determine the required PPE for the task. Table 130.7(C)(16) lists the requirements for PPE based on arc flash PPE categories 1 through 4. This clothing and equipment shall be used when working within the arc flash boundary.

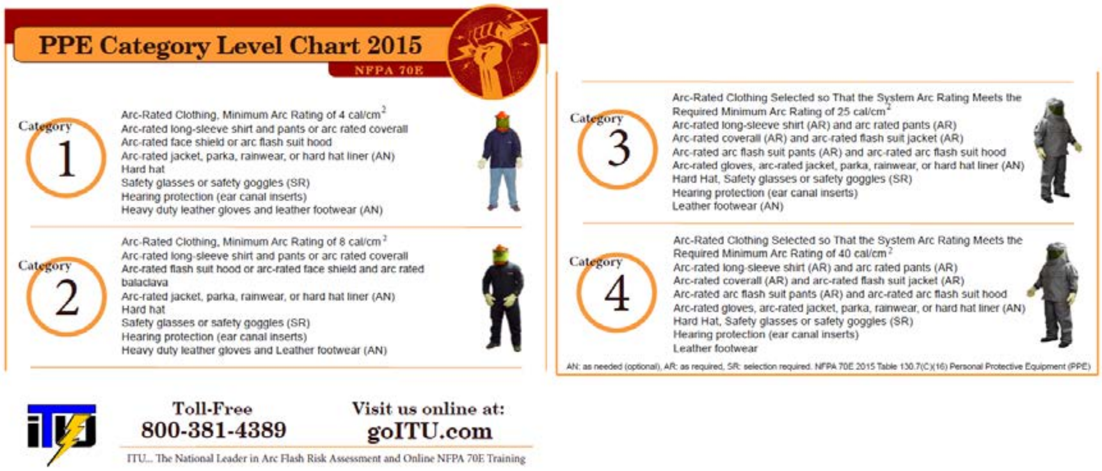


Figure 48: NFPA Table 130.7 (C) (16) PPE from goITU.com

It should be noted again that 1.2 Cal/cm^2 is the threshold of a second degree burn. Arc flash protection is designed to limit the injury to no more than a “just curable” second degree burn. You can still be burned by abiding by the rules [49]. The Category 4 PPE is not intended to protect under all conditions but rather only up to a limit of 40 Cal/cm^2. Many arc flashes produce energy far in excess of 40 Cal/cm^2 with energy values in the hundreds of Cal/cm^2. The PPE categories only provide protection for the effects of the heat. They do not provide protection for the flying shrapnel, molten metal, pressure wave or from electric shock. As a reference:

- 1st degree burns affect the outer layer of skin, it is painful, but not usually permanent or life threatening
- 2nd degree burns cause tissue damage and blistering. The outer skin layer is destroyed.
- 3rd degree burns cause the complete destruction of skin. Small areas may recover, large areas will need skin grafting [49]

Photos of 2nd degree and 3rd degree burns:

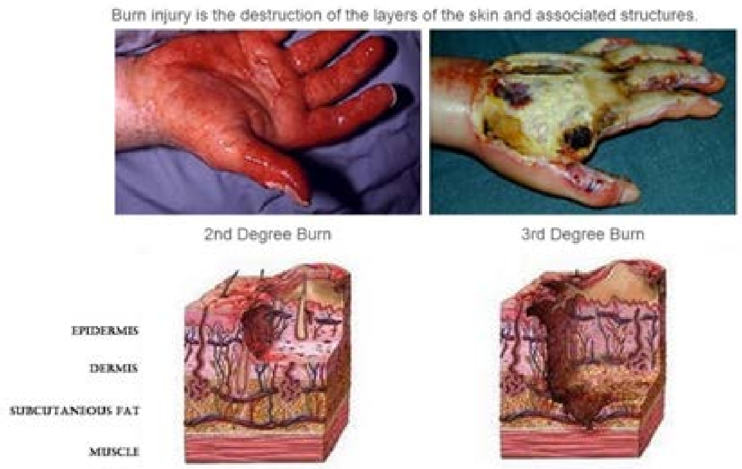


Figure 49: Classification Of Burn Injuries – from ref [64]

4.5 PROCEDURE ALGORITHM FOR ARC FLASH HAZARD ANALYSIS

Section 4 of IEEE 1584 suggests a nine-step approach to arc flash hazard analysis. The following contain a brief synopsis of each step. Be advised to refer to IEEE 1584 for more information and be certain to read the cautions and disclaimers carefully.

Step 1: Collect System and Installation Data

The data needed for an arc flash hazard analysis is similar to that needed for a short circuit and coordination study (refer to Appendix III). Collecting system data is the most difficult and time-intensive step in performing an arc flash hazard analysis, but accurate information is vital to correctly calculating flash boundaries. A relatively small error at this point can invalidate all further arc flash calculations. Information collected should be recorded on a one-line diagram of the facility's electrical system. This diagram should be updated whenever modifications are made to the system [58, 59].

Step 2: Determine System Modes of Operation

Many electrical systems, especially in smaller facilities, have only a single mode of operation. In large facilities, however, it is common to find a number of operating modes, possibly including: emergency modes in which only backup generators provide power; multiple utility sources or generators that are switched in or out; tie breakers opened or closed, and motors or portions of the system that may start or cease operation. As noted in Step 1, the highest available fault current may not yield the worst-case arc flash energy, since the worst-case energy also depends on the opening time of the overcurrent protection devices. All of these different modes cause changes in current at various points in the system, altering incident energy and flash boundaries [58, 59].

Step 3: Determine Bolted Fault Currents

A Short Circuit Study is required to determine the magnitude of current flowing throughout the power system at critical points at various time intervals after a “fault” occurs. These calculations will be used to determine the bolted fault current. The bolted fault current is the current that would flow through a short circuit consisting of two conductors bolted together. It is the maximum current available to flow through a short circuit. This information is used to calculate the arc fault currents. Bolted fault currents should be determined for each piece of equipment likely to require maintenance or inspection while energized. The bolted fault currents are calculated from the data gathered in Step 1 and Step 2. Refer to IEEE Standard 141 (Red Book) for details on methodology pertaining to these calculations. The typical method is to enter the data into a commercially available software program that allows you to model your system and easily switch between modes of operation [58, 59].

Step 4: Determine Arc Fault Currents

The current that flows through an arcing fault is usually significantly less than the bolted fault current, due to greater resistance. The bolted fault current calculated for each point in the system represents the highest possible fault current expected to flow to that point. In the case of an arcing fault, the current flow to the fault will be less, due to the added impedance of the arc. It is important to adequately predict these lower current levels, especially if the overcurrent protective devices are significantly slower at these reduced levels, as these situations have been known to provide worst-case arc fault hazards. Arc fault current calculations are based on voltage, bolted fault current, conductor gap distance, and other factors. IEEE 1584 presents two formulas for calculating arc fault currents, one for use with 0.208 to 1 kV systems, and the other for systems between 1 and 15 kV (refer to section 4.6 of this chapter) [58, 59].

Step 5: Find Protective Device Characteristics and Duration of Arcs

A Protective Device Coordination Study should be performed to ensure selection and arrangement of protective devices limits the effects of an overcurrent situation to the smallest area. Results will be used to make recommendations for mitigation of arc flash hazards. The time-current curves of upstream protective devices are the major factor in determining how long an arc-fault will last. An effort should be made to determine the actual settings rather than relying on standard values, as these may cause incident energy to vary greatly [58, 59].

Another consideration when analyzing protective devices is that incident energy depends on both fault current and time. Since protective devices are slower at lower currents, minimum fault currents often pose the worst-case arc flash scenario [58, 59].

Step 6: Document System Voltages and Classes of Equipment

Factors that affect arc energies, such as bus gap and voltage, are required for IEEE 1584 equations. A table is provided with typical bus gaps for various equipment up to 15kV (refer to section 4.6 of this chapter) [58, 59].

Step 7: Select Working Distances

The working distance is the distance from a potential arc source to a worker's face and chest. It is a critical quantity in determining the flash hazard boundary, as even an increase of a few inches in working distance can cause a significant drop in incident energy. Incident energy on a worker’s hands and arms would likely be higher in the event of an arcing fault because of their closer proximity to the arc source. 18 inches is the working distance most commonly assumed in calculations, but efforts should be made to determine actual working distances [58, 59].

Step 8: Determine Incident Energy for All Equipment

Incident energy is defined in NFPA 70E as "the amount of energy impressed on a surface, a certain distance from the source, generated during an electrical arc event." In an arc flash hazard study, the "surface" is the worker's body at the assumed working distance. Incident energy is expressed in Cal/cm^2. The analyst will need to choose equations based upon voltage level, type of overcurrent protective device and equipment. In addition to the current limiting fuse equations, the IEEE guide provides other equations that call for the data described above. Because of the complexity and number of manual calculations possible, software is recommended to complete this step. Most software gives you a choice of equations, including three other incident energy equations (refer to section 4.6 of this chapter) [58, 59].

Step 9: Determine Flash Protection Boundary for All Equipment

Instead of solving for Cal/cm^2 at a given working distance, this equation solves for a distance at which the incident heat energy density would be 1.2 Cal/cm^2 (or 5 Joules/cm^2). Due to the same reasons mentioned in Step 8, software is also recommended for this calculation [58, 59].

4.6 ARC FLASH HAZARD ANALYSIS METHOD – IEEE STANDARD 1584

IEEE Standard 1584-2002 contains calculation methods developed through testing by several sources to determine boundary distances for unprotected personnel and the incident energy at the working distance for qualified personnel working on energized equipment. The incident energy level can be used to determine the proper PPE required for personnel [48].

The equations developed in the IEEE standard assess the arc flash hazard based on the available bolted fault current, voltage, clearing time, equipment type, grounding, and working distance. The working voltage is also used to determine other variables. The equations account for grounding, equipment type, and construction. This method can also determine the impact of some classes of current limiting low voltage fuses as well as certain types of low voltage breakers. The calculations can be applied over a large range of voltages [48].

The many variables of this method make it the preferred choice for Arc Flash evaluations, but at the same time requires either a complex spreadsheet or computer program to be used efficiently.

- The Equations For Arc Flash Incident Energy Calculations Are Found In Appendix IV (Extracted from Section 5 of IEEE 1584-2002).

- Solved example in Appendix V from Thomas Smith. Courtesy of Power System Analysis– NOTE: Calculation performed prior to 2015 Revision of NFPA 70E.

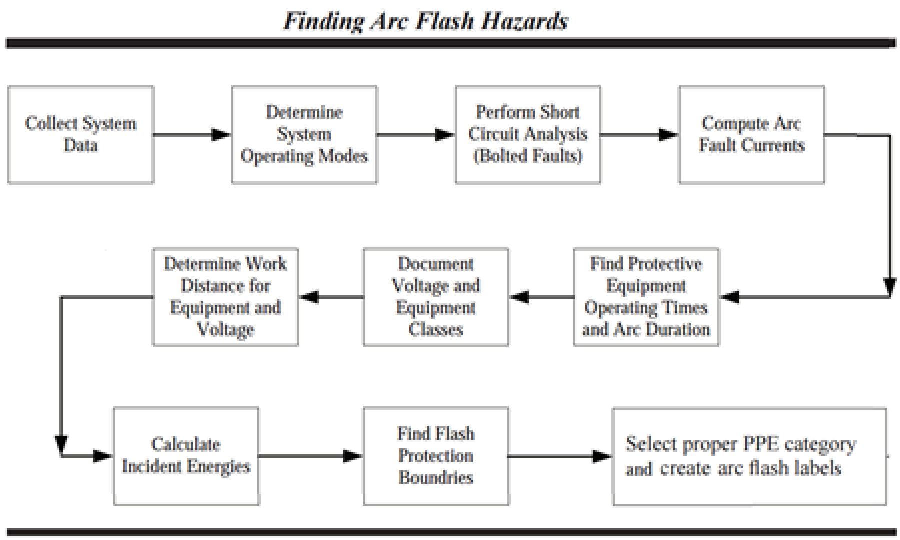


Figure 50: Procedure for Comprehensive Arc Flash Hazard Risk Assessment

4.7 ANATOMY OF ARC FLASH LABELS

The 2002 edition of the NEC introduced a requirement that most electrical equipment be field marked to warn of potential arc flash hazards [54]. Each piece of equipment operating at 50 Volts or more and not put into a de-energized state must be evaluated for arc flash and shock protection. This evaluation will determine the actual boundaries and will inform the employee of what PPE must be worn.

Once the evaluation is complete an Arc Flash Hazard warning label must be affixed to the equipment and readily accessible to employees who may work on the energized equipment [50]. The 2015 edition of the NEC made minor changes to the 2011 version and now reads [47]:

“110.16 Arc flash Hazard Warning

Electrical equipment, such as switchboards, switchgear, panelboards, industrial control panels, meter socket enclosures, and motor control centers, that are in other than dwelling units, and are likely to require examination, adjustment, servicing, or maintenance while energized, shall be field or factory marked to warn qualified persons of potential electric arc flash hazards. The marking shall meet the requirements in 110.21(B) and shall be located so as to be clearly visible to qualified persons before examination, adjustment, servicing, or maintenance of the equipment”.

NFPA 70E-2015, provides assistance in determining severity of potential exposure, planning safe work practices, and selecting personal protective equipment. A similar requirement is included in Article 130.5 (D) of NFPA 70E-2015, as follows [41]:

“130.5 (D) Equipment Labeling

Electrical equipment such as switchboards, panelboards, industrial control panels, meter socket enclosures, and motor control centers that are in other than dwelling units and that are likely to require examination, adjustment, servicing, or maintenance while energized shall be field-marked with a label containing all the following information:

(1) Nominal system voltage

(2) Arc flash boundary

(3) At least one of the following:

a. Available incident energy and the corresponding working distance, or the arc flash PPE category in Table 130.7(C)(15)(A)(b) or Table 130.7(C)(15)(B) for the equipment, but not both

b. Minimum arc rating of clothing

c. Site-specific level of PPE

Exception: Labels applied prior to September 30, 2011 are acceptable if they contain the available incident energy or required level of PPE.

The method of calculating and the data to support the information for the label shall be documented. Where the review of the arc flash hazard risk assessment identifies a change that renders the label inaccurate, the label shall be updated. The owner of the electrical equipment shall be responsible for the documentation, installation, and maintenance of the field-marked label".

The American National Standard Institute (ANSI) is the organization responsible for publishing the ANSI Z535 series of standards. The ANSI Z535.4 Standard, titled *Product Safety Signs and Labels,* defines the content for a safety label. ANSI Z535.4 offers two header options or *signal words* to classify the relative seriousness of the hazardous location – based on the probability of being injured if the hazard is not avoided, and on the severity of the resulting injury i.e., A "DANGER" header with white letters on a red background or a "WARNING" header with black letters on an orange background – refer to Figure 51 [51, 52, and 53].

The “DANGER” header indicates a hazardous situation which, if not avoided, will result in death or serious injury. This signal word is to be limited to the most extreme situations - calculated incident energy greater than 40 Cal/cm^2. The “WARNING” header indicates a hazardous situation which, if not avoided, could result in death or serious injury - calculated incident energy less than 40 Cal/cm^2. The header option should be go together with its *safety alert symbol* -- a symbol that indicates a hazard. It is composed of an equilateral triangle surrounding an exclamation mark. The safety alert symbol is only used on hazard alerting signs [51, 52, and 53].

Figure 51: Safety Alert Symbols – from ANSI Z535.4

Symbol (A) for use with **DANGER** signal word; (safety white triangle, safety red exclamation mark, safety red background)
Symbol (B) for use with **WARNING** signal word; (safety black triangle, safety orange exclamation mark)

Finally, the labels must have UL 969 standard compliance for durability and adhesion. Note: The NFPA does not specify whether the sign must use a

"DANGER" or "WARNING" header nor set forth requirements for the design or sign layout, but refers to ANSI Z535.4 for guidelines on the design [55].

SAMPLE ARC FLASH LABELS – Courtesy of **POWERSTUDIES.com, EMERSON,** and **MARTIN TECHNICAL**:

Figures 52 and 53 are two examples of labels generated using the arc flash module in a power systems analysis software tool. Images are courtesy of PowerStudies.com, Emerson and Martin Technical.

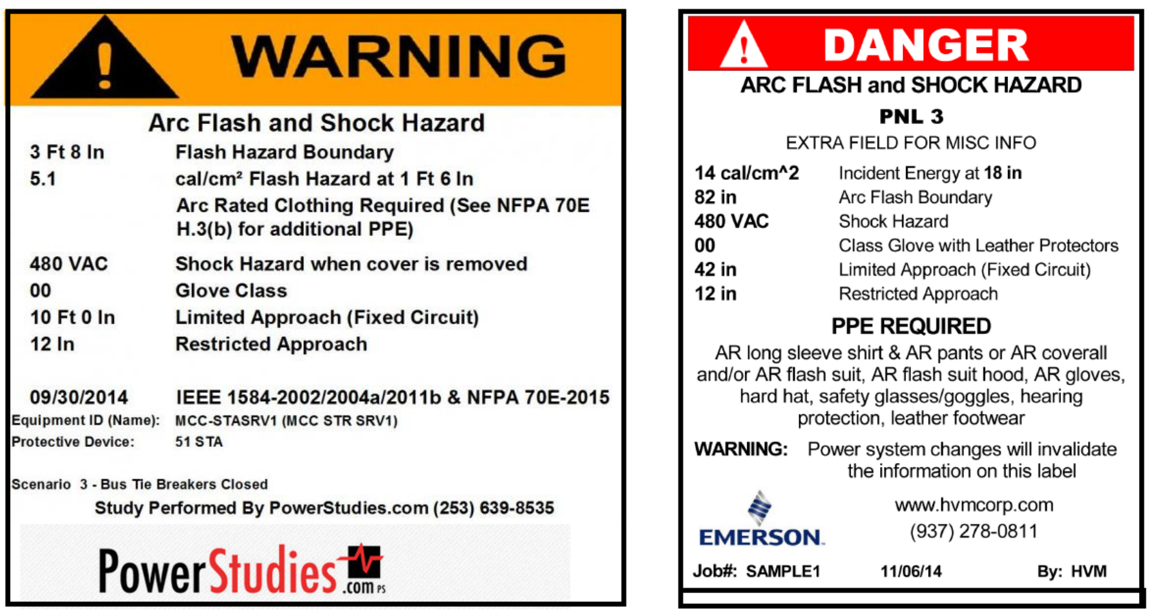


Figure 52: Arc Flash Labels from PowerStudies.com and Emerson

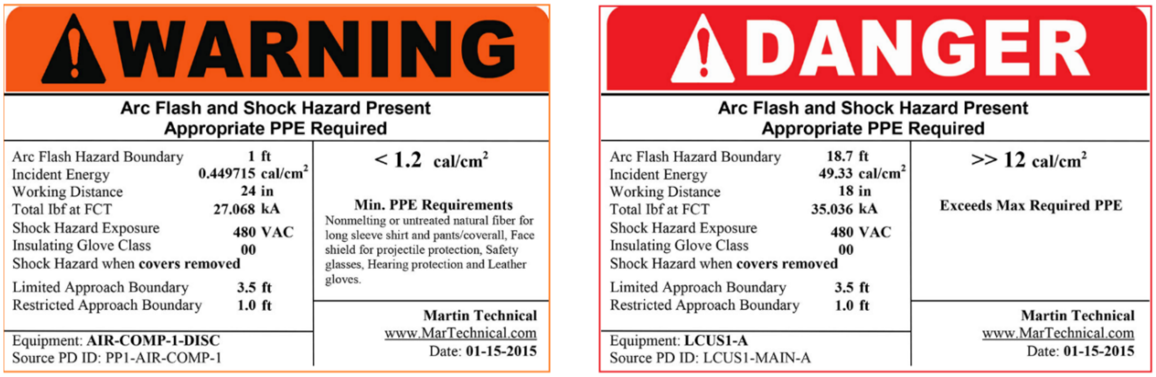


Figure 53: Arc Flash Labels from Martin Technical

We observe that the labels on the right indicate prohibited work - incident energy is far above the 40 Cal/cm^2 limit for energized work. In addition to the incident energy information, the labels also include required glove classification and the shock protection boundaries required by NFPA 70E. Since these labels are part of a certified process, they include who performed the work and on what date. Documenting and dating Arc Flash Warning labels is imperative because NFPA 70E-2015 Article 130.5 states that “An arc flash risk assessment shall be performed and updated when a major modification or renovation takes place. It shall be reviewed periodically, at intervals not to exceed 5 years, to account for changes in the electrical distribution system that could affect the results of the arc flash risk assessment”.

CHAPTER 5 ELECTRICAL POWER SYSTEMS STUDIES FOR THE KAMAMA PUMP STATION

5.1 EXECUTIVE SUMMARY

5.1.1 Overview – Purpose of Study

When the electrical power distribution system is modified and upgraded in a facility like the KAMAMA Pump Station in Katia, Texana; a comprehensive power system analysis should be performed.

The first step is to conduct a short-circuit study. This study confirms that all circuit breakers, switchgears, motor control centers, panel boards, fuses and other protective devices within the scope of the study are properly rated for the maximum system fault current. The short-circuit study is documented in Section 5.3.

A protective device coordination study is necessary in order to provide recommended device settings for the adjustable circuit breakers and relays. This study is documented in Section 5.4.

Finally, an arc flash study is contained in Section 5.5. The results of the short-circuit and coordination studies are utilized to determine the arc flash boundaries, incident energies and protective clothing classes for the equipment locations within the scope of this study. Equipment arc flash labels have been produced indicating the type of protective clothing that is to be worn when working on electrical equipment within the facility.

5.1.2 Summary of Study Results

(1) In the short-circuit study, all equipment locations were evaluated for adequacy to interrupt or withstand the maximum three phase fault current to which they could be subjected. All equipment PASSED the Evaluation Study - the tables in Attachments III, IV, V and VI verify that all of the evaluated equipment is applied within the equipment fault ratings.

(2) The coordination study has in general provided a high level of selectivity among the power system protective devices. The coordination study showed for the most part, acceptable levels of selectivity were achieved among devices in the system. The devices have been optimized to provide the highest level of selectivity possible for the equipment and system design. It also displays the overcurrent protection of major components such as cables, transformers and motors. The breakers and relays in the system should be set to the recommended levels found in the device setting sheet in Attachment XII. Refer to Section 5.4.1 for a detailed discussion.

(3) All equipment locations were analyzed to determine the amount of arc flash incident energy to which a worker might be exposed during an arc flash event. PPE category 1 and 2 are present on the arc flash labels created for the equipment. The results of the arc flash analysis show both the calculated arc flash incident energy and flash protection boundary distances at each bus under study. There were two arc flash fault current scenarios considered. The first consisted of a utility source (2067 Amps at 24900V, based on a maximum fault current). The second was a generator source for equipment fed by the

emergency generator. The results of all the scenarios were combined into one composite table showing the worst case results for each piece of equipment evaluated.

The arc flash hazard analysis and recommended PPE levels are no substitutes for safe work practices. As stated in NFPA 70E, burn injuries can occur even when adequate PPE is employed, and the recommended PPE may provide little or no protection against arc blast and its effects. Protection from arc flash can best be provided by working only on circuits or equipment that have been placed in an electrically safe work condition. Work should not be performed on or near equipment listed “Dangerous” unless it has been placed in an electrically safe work condition.

All Studies were performed at using the DAPPER, CAPTOR and A_FAULT modules of *SKM Power Tools for Windows* Software, version 7.0.4.

5.2 ELECTRICAL SYSTEM DESCRIPTION

The electrical reliability package of the modification of the KAMAMA Pump Station comprised mainly of the addition of two 800 HP motor pumps. The facility upgrade therefore included the addition of a new motor control center MMC-B-WEST, new transformer XFMR-B-WEST and switchgear SWG N2-WEST to be fed from existing transformer XFMR-N2-WEST. To prepare for the possible outage of Utility power, a new 2250 KW Standby Generator will keep the motors running.

There are two modes of operation or scenarios considered for the arc flash study. The first consist of a Utility source (Normal operation mode). The second is a generator source for equipment fed by the Standby generator (Emergency operation mode). During normal operation, breakers 1200A-VCP-W-BT1 and 1200A-VCP-W-BT2 are offline. In Emergency mode, they switch to “in-service status” on the loss of utility power to energize switchgears SWGR N1-EAST and SWGR N2-WEST when the generator is running.

Accurate data about the power system is essential for any system study to accurately predict its behavior. Sometimes even seemingly insignificant errors in the system data can produce significant errors in the study results. This is especially the case with an arc flash hazard analysis. A single line diagram will show how the main components of the electrical system are connected. It shows the power distribution path from the power source(s) to each downstream load – including the ratings and sizes of each piece of electrical equipment, their feeder conductors, and their protective devices. The single-line diagram associated with the scope of the expansion of the power distribution system of the KAMAMA Pump Station is shown is Section 5.3.3. Refer to Section 5.2.1 for component input data.

5.2.1 Input Data – Normal and Emergency Operation

Attachment I – Input Data – Normal Operation

Attachment II – Input Data – Emergency Operation

5.3 SHORT CIRCUIT ANALYSIS STUDY

Short-circuit analysis is done to determine the magnitude of the prospective currents flowing throughout the power system at various time intervals after a fault occurs. The magnitude of the currents flowing through the power system after a fault varies with time until they reach a steady-state condition. During this time, the protective system is called on to detect, interrupt, and isolate these faults.

Short-circuit momentary duties and interrupting duties imposed on the equipment is dependent upon the magnitude of the current, which is dependent on the time from fault inception. This is calculated at each switchgear bus, switchboard, motor control center, distribution panel board, and other significant locations throughout the system. The information is used to select fuses, breakers, and switchgear ratings in addition to setting protective relays.

The short circuit data is used to determine the bolted three-phase short circuit current, which is in turn used to calculate the arcing fault current. The short circuit analysis is required for proper sizing of circuit breakers and/or fuses. Three-phase and line-to ground fault studies were performed. The A_FAULT module of the *SKM Power Tools for Windows* Software performs fault calculations in full compliance with the ANSI C37 standards C37.13, C37.010, and C37.5.

Hence: The purpose of a short circuit study is to identify the maximum available fault current at all locations, called busses, in the power system. It is then compared with the ratings of the individual power system components to determine if the equipment is adequately rated to safely withstand or interrupt the calculated fault current. The results of the short circuit study are also used in both the coordination study and the arc flash study.

5.3.1 Short-Circuit Study Results

The Normal and Standby operation modes for the maximum possible fault conditions were both evaluated. The Equipment Evaluation Tables, found in Attachments III, IV, V and VI, summarizes fault duties on circuit breakers and fuses. Then it verifies if the ratings of the equipment being supplied meets or exceeds the required ratings. Attachments VII and VIII shows the one line diagrams with ratings of all equipment buses (panel boards, MCC's, switchboards and switchgear) and their corresponding calculated three-phase fault current and/or MVA. Attachments IX and X are detailed short circuit output reports.

5.3.2 Equipment Evaluation Tables – Device & Panel

Attachment III - Panel Evaluation-Normal Operation

Attachment IV - Device Evaluation-Normal Operation

Attachment V - Panel Evaluation-Emergency Operation

Attachment VI - Device Evaluation- Emergency Operation

5.3.3 Short-Circuit Study One-Line Diagrams – Normal & Emergency Operation

Attachment VII - Short-Circuit Study One-Line Diagram – Normal Operation

Attachment VIII - Short-Circuit Study One-Line Diagram – Emergency Operation

5.3.4 Short-Circuit Computer Output Reports – Normal & Emergency Operation

Attachment IX - Short-Circuit Study Computer Output Report – Normal Operation

Attachment X - Short-Circuit Study Computer Output Report – Emergency Operation

5.4 PROTECTIVE DEVICE COORDINATION STUDY

The objective of a protection scheme in a power system is to minimize hazards to personnel and equipment while allowing the least disruption of power service. Coordination studies are required to select or verify the clearing characteristics of devices such as fuses, circuit breakers, and relays used in the protection scheme. These studies are also needed to determine the protective device settings that will provide selective fault isolation. In a properly coordinated system, a fault results in interruption of only the minimum amount of equipment necessary to isolate the faulted portion of the system. The power supply to loads in the remainder of the system is maintained. The goal is to achieve an optimum balance between equipment protection and selective fault isolation that is consistent with the operating requirements of the overall power system.

Short-circuit calculations are a prerequisite for a coordination study. Short-circuit results establish minimum and maximum current levels at which coordination must be achieved and which aid in setting or selecting the devices for adequate protection. When facilities are changed or upgraded, it is necessary to revisit the existing protection scheme to determine if change is needed to be made to ensure that devices are coordinated properly. A change in load or equipment could change the timing and coordination of the protective devices.

Hence: The purpose of a Protective Device Coordination study is to determine the proper settings for overcurrent protective devices in the power system. A Coordination Study will show you the probable and possible values of fault currents within the system and show you impact short circuits and failures would have on your fuses, circuit breakers, and your facility's operation. Ideally the selection of the proper settings will both protect the power system equipment as well as remove only the smallest portion of the electrical system as necessary from service in order to isolate a fault. In most cases however, compromises must be made in order to provide the best overall system reliability.

5.4.1 Discussion of Coordination Study

In order to determine the proper setting for the overcurrent protective devices, they are plotted on time-current curve graphs (TCCs). The CAPTOR module of the SKM Power*Tools Software was used to complete the device coordination analysis.

The TCCs in Attachment XI show select coordination curves of the KAMAMA Pump Station power system. As shown from the TCCs, the protective devices in the system provide acceptably good coordination. Comments on the specific TCC graphs as applicable are given below:

1) TCC # 01: SWGR N1-EAST PROTECTION

This curve provides the coordination from the Cooper iDP-210 Relay on the Cooper iDP-210 Switchgear and Cooper VFI Tri-Phase Control Switch on the existing 25KV Switchgear through the Cooper VFI Tri-Phase Control Switch on the primary of the XFMR-N1-EAST down to the N1-M3520 Beckwith Main and the GE Multilin BT1-MIF-II Tie relays on SWGR N1-EAST. Coordination has been achieved. Cable protection is excellent.

2) TCC # 02: PUMP #1-EAST PROTECTION

This curve provides the coordination from GE Multilin BT1-MIF-II Tie and the D1-MIF-II feeder relays on SWGR N1-EAST down to the 400E main and the EJ2-6R feeder fuses on MCC-A-EAST feeding SR-369 motor protection relay which feeds Pump#1-EAST. Coordination has been achieved. Cable protection is excellent.

3) TCC # 03: PUMP #3-WEST PROTECTION

This curve provides the coordination from GE Multilin BT1-MIF-II Tie and the D2-MIF-II feeder relays on SWGR N2-WEST down to the 400E main and the EJ2-9R feeder fuses on MCC-B-WEST feeding SR-369 motor protection relay which feeds Pump#3-WEST. Coordination has been achieved. Cable protection is excellent.

4) TCC # 04: GENERATOR MCC-B-WEST PROTECTION

This curve provides the coordination from the GE Multilin SR-489 Generator Protection Relay, BT2-MIF-II Generator Tie relay and D2-MIF-II feeder relay on SWGR N2-WEST feeding MCCB. Coordination has been achieved. Cable protection is excellent.

5) TCC # 05: SWGR N1-EAST GROUND FAULT PROTECTION

This curve provides the 4160V ground fault coordination between the main, Tie and the feeders on SWGR N1-EAST. Coordination has been achieved.

6) TCC # 06: GENERATOR-1 GROUND FAULT PROTECTION

This curve provides the 4160V ground fault coordination between the Generator main, tie and the feeder relays. Coordination has been achieved.

Attachment XI - All TCC Coordination Graphs

Attachment XII - Device Settings Sheet

5.5 ARC FLASH ANALYSIS STUDY

In the early 1980's, a paper "The Other Electrical Hazard: Electric Arc Blast Burns" by Ralph Lee was published in the IEEE Transactions on Industrial

Applications. The effect of this paper was to realize the need to protect people from the hazards of arc flash. Four separate industry standards concern the prevention of arc flash incidents:

- OSHA 29 Code of Federal Regulations (CFR) Part 1910 Subpart S
- NFPA 70-2014 National Electrical Code (NEC)
- NFPA 70E-2015 Standard for Electrical Safety Requirements for Employee Workplaces
- IEEE Standard 1584-2004 Guide for Performing Arc Flash Hazard Calculations

Compliance with OSHA involves adherence to a six-point plan:

- A facility must provide, and be able to demonstrate, a safety program with defined responsibilities
- Calculations for the degree of arc flash hazard
- Correct personal protective equipment (PPE) for workers
- Training for workers on the hazards of arc flash
- Appropriate tools for safe working
- Warning labels on equipment

Arc flash Hazard Analysis calculates the incident energy and arc flash boundary for each location in a power system so that electrical workers are aware of the potential hazard and can make informed choices about personal protective equipment. Trip times of protective device settings obtained from coordination studies and arcing fault current values from the short circuit analysis are used in arc flash hazards analysis. Incident energy and arc flash boundaries are calculated following the NFPA 70E or IEEE 1584 Standards.

Once again, multiple operating scenarios (Normal mode and Standby mode) were considered in order to properly calculate the incident energy levels in the system. Unlike short circuit studies where we are concerned with the maximum available fault current, with arc flash studies we are really concerned with all possible available fault currents. In many cases the highest incident energy levels are produced by the scenario that produces the lowest available fault current. This is because fault currents that fall just below the instantaneous or short time pickup of circuit breakers will last for a much longer time period and therefore expose an electrical worker to more energy.

Arc flash Hazard Warning Labels showing flash protection boundary, incident energy, arc resistant clothing required, and other valuable information system mandated by the NEC and NFPA 70E Standards will be printed on stick-on labels to be easily placed on equipment. The label tags will display the worst-case incident energy levels based on the arc flash study results from both operating scenarios.

5.5.1 Arc Flash Study Results

The Arc Fault study indicated that there are two locations classified as PPE Category 1. All other locations are classified as PPE Category 2.

5.5.2 Arc Flash Study One-Line Diagrams – Normal & Emergency Operation

Attachment XIII - Arc Flash Study One-Line Diagrams – Normal Operation

Attachment XIV - Arc Flash Study One-Line Diagrams – Emergency Operation

5.5.3 Arc Flash Study Computer Output Reports – Normal & Emergency Operation

Attachment XV - Arc Flash Study Computer Output Report – Normal Operation

Attachment XVI - Arc Flash Study Computer Output Report – Emergency Operation

5.5.4 Arc Flash Warning Labels

Attachment XVII – All Arc Flash Labels

DISCLAIMER

- Modification of equipment, changes to system configuration, adjustment of protective device settings, or failure to properly maintain equipment may invalidate these results. If changes are made to the electrical system, then the arc flash study and the arc flash labels are no longer valid and a new arc flash study must be performed.
- The project name, facility location and equipment ID tags were changed for the purpose of this report.

Chapter 6 CONCLUSION, FUTURE WORK AND FOCUS

CONCLUSION

The case study of the modification of the KAMAMA Pump Station in Katia, Texana; illustrated the interpretation of design standards and codes utilized in performing comprehensive short-circuit analysis, protective device coordination and arc flash hazard risk assessments.

The short-circuit analysis evaluated new electrical equipment to be installed. All circuit breakers, switchgears, motor control centers, panel boards, fuses and other protective devices considered in the study passed the evaluation.

The protection coordination study reviewed the selectivity and discrimination among the new and existing protective devices within the facility. A record sheet was provided to recommend device settings for the adjustable circuit breakers and relays.

The arc flash analysis assessed the magnitude of the incident energies at vital locations considered in the short circuit analysis. Equipment arc flash labels were created to inform qualified personnel of the required PPE to be worn during equipment maintenance.

The subjects presented in this thesis act as an introductory material to readers interested in exploring and learning about the significance of power system studies and arc flash hazards in commercial and industrial facilities. The information presented here are summaries obtained from numerous references.

Engineers and Field Technicians new to this subject are strongly advised to further read the relevant electrical engineering textbooks and governing industry standards (NEC/NFPA, NFPA 70E, IEEE), accompanied by formal education and training to have an appreciation of the significance of co-dependent system studies relevant to IEEE Standard1584.

FUTURE WORK AND FOCUS

Compliant engineering design is just part of the solution to address arc flash mitigation. Adopting on-site preventive maintenance methods like periodic inspection and comprehensive mechanical/electrical testing of equipment help extend life expectancy and ensure operating efficiency of the facility.

Moreover, appropriate safety training mandated by the NFPA 70E should be supervised and conducted by instructors who are experienced and OSHA qualified. Facilities should also be willing to explore new products to reduce arc flash hazards such as installing fast-acting fuses, remote racking, arc resistant switchgears/MCCs, utilizing low arc flash circuit breakers, using infrared scanning windows on switchgears/MCCs, etc. The industry should also be on the lookout for innovations in clothing and textiles technology to better specify arc-rated protective apparel.

ATTACHMENTS

Attachment I – Input Data – Normal Operation

Attachment II – Input Data – Emergency Operation

Attachment III - Panel Evaluation-Normal Operation

Attachment IV - Device Evaluation-Normal Operation

Attachment V - Panel Evaluation-Emergency Operation

Attachment VI - Device Evaluation- Emergency Operation

Attachment VII - Short-Circuit Study One-Line Diagram – Normal Operation

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Attachment IX - Short-Circuit Study Computer Output Report – Normal Operation

Attachment X - Short-Circuit Study Computer Output Report – Emergency Operation

Attachment XI - All TCC Coordination Graphs

Attachment XII - Device Settings Sheet

Attachment XIII - Arc Flash Study One-Line Diagrams – Normal Operation

Attachment XIV - Arc Flash Study One-Line Diagrams – Emergency Operation

Attachment XV - Arc Flash Study Computer Output Report – Normal Operation

Attachment XVI - Arc Flash Study Computer Output Report – Emergency Operation

Attachment XVII – All Arc Flash Labels

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APPENDIX

Appendix I - Per Unit Method –from Reference [9]

Appendix II - ANSI Method - from Reference [27]

Appendix III – Required Data for Arc Flash Analysis – from BICE Engineering and Consulting

Appendix IV - Section 5 of IEEE 1584-2002

Appendix V - Example for IEEE 1584 Method - from Reference [27]

KAMAMA PUMP STATION
KATIA, TEXANA

SKM POWER*TOOLS FOR WINDOWS
INPUT DATA REPORT

ALL PU VALUES ARE EXPRESSED ON A 100 MVA BASE.

FEEDER INPUT DATA

CABLE	FEEDER FROM	FEEDER TO	QTY	VOLTS	LENGTH	FEEDER

Attachment I – Input Data – Normal Operation

```
 NAME          NAME            NAME            PH  L-L                    SIZE       TYPE

========================================================================================================
===
 1/0-1-475-1   25KV SWGR EXIS  XFMR- N2 PRI     1  24900  475.0  FEET     1/0     Copper
               Duct Material: Non-Magnetic     Insulation Type:         EPR     Insulation Class:         MV
               +/-  Impedance: 0.1280 + J  0.0507  Ohms/1000 ft      0.0098 + J  0.0039  PU
               Z0   Impedance: 0.2035 + J  0.1290  Ohms/1000 ft      0.0156 + J  0.0099  PU

 1/0-1-495-2   25KV SWGR EXIS  XFMR - N1 PRI    1  24900  495.0  FEET     1/0     Copper
               Duct Material: Non-Magnetic     Insulation Type:         EPR     Insulation Class:         MV
               +/-  Impedance: 0.1280 + J  0.0507  Ohms/1000 ft      0.0102 + J  0.0040  PU
               Z0   Impedance: 0.2035 + J  0.1290  Ohms/1000 ft      0.0162 + J  0.0103  PU

 1-1-110-3     MCC-B-WEST     PUMP 4            1   4160  110.0  FEET       1     Copper
               Duct Material: Non-Magnetic     Insulation Type:         EPR     Insulation Class:         MV
               +/-  Impedance: 0.1600 + J  0.0456  Ohms/1000 ft      0.1017 + J  0.0290  PU
               Z0   Impedance: 0.2543 + J  0.1160  Ohms/1000 ft      0.1616 + J  0.0737  PU

 1-1-65-2      MCC-A-EAST      PUMP 2           1   4160   65.0  FEET       1     Copper
               Duct Material: Non-Magnetic     Insulation Type:         EPR     Insulation Class:         MV
               +/-  Impedance: 0.1600 + J  0.0456  Ohms/1000 ft      0.0601 + J  0.0171  PU
               Z0   Impedance: 0.2543 + J  0.1160  Ohms/1000 ft      0.0955 + J  0.0436  PU

 2-1-100-4     MCC-A-EAST      XFMR-A PRI       1   4160  100.0  FEET       2     Copper
               Duct Material: Non-Magnetic     Insulation Type:         EPR     Insulation Class:         MV
               +/-  Impedance: 0.2020 + J  0.0467  Ohms/1000 ft      0.1167 + J  0.0270  PU
               Z0   Impedance: 0.3211 + J  0.1188  Ohms/1000 ft      0.1855 + J  0.0686  PU

 2-1-125-1     MCC-B-WEST     PUMP 3            1   4160  125.0  FEET       2     Copper
               Duct Material: Non-Magnetic     Insulation Type:         EPR     Insulation Class:         MV
               +/-  Impedance: 0.2020 + J  0.0467  Ohms/1000 ft      0.1459 + J  0.0337  PU
               Z0   Impedance: 0.3211 + J  0.1188  Ohms/1000 ft      0.2319 + J  0.0858  PU

 2-1-20-5      MCC-A-EAST      VFD P1 IN        1   4160   20.0  FEET       2     Copper
               Duct Material: Non-Magnetic     Insulation Type:         EPR     Insulation Class:         MV
               +/-  Impedance: 0.2020 + J  0.0467  Ohms/1000 ft      0.0233 + J  0.0054  PU
               Z0   Impedance: 0.3211 + J  0.1188  Ohms/1000 ft      0.0371 + J  0.0137  PU

 2-1-50-4      VFD-P1 OUT      PUMP1            1   4160   50.0  FEET       2     Copper
               Duct Material: Non-Magnetic     Insulation Type:         EPR     Insulation Class:         MV
               +/-  Impedance: 0.2020 + J  0.0467  Ohms/1000 ft      0.0584 + J  0.0135  PU
               Z0   Impedance: 0.3211 + J  0.1188  Ohms/1000 ft      0.0928 + J  0.0343  PU

 2-1-85-1      MCC-B-WEST      XFMR-B PRI       1   4160   85.0  FEET       2     Copper
               Duct Material: Non-Magnetic     Insulation Type:         EPR     Insulation Class:         MV
               +/-  Impedance: 0.2020 + J  0.0467  Ohms/1000 ft      0.0992 + J  0.0229  PU
               Z0   Impedance: 0.3211 + J  0.1188  Ohms/1000 ft      0.1577 + J  0.0584  PU
```

FEEDER INPUT DATA

```
=================================================================================================
===
 CABLE          FEEDER FROM     FEEDER TO       QTY  VOLTS   LENGTH           FEEDER
 NAME           NAME            NAME            /PH  L-L                  SIZE       TYPE

=================================================================================================
===
 3/0-1-1        UTIL            COOPER iDP-210   1  24900  1.000  FEET     3/0     Copper
                Duct Material: Non-Magnetic     Insulation Type:        EPR     Insulation Class:         MV
                +/-  Impedance: 0.0805 + J  0.0484  Ohms/1000 ft     0.00001 + J 0.00001  PU
                Z0   Impedance: 0.1279 + J  0.1230  Ohms/1000 ft     0.00002 + J 0.00002  PU

 3/0-1-30-1     COOPER iDP-210  25KV SWGR EXIS   1  24900   30.0  FEET     3/0     Copper
                Duct Material: Non-Magnetic     Insulation Type:        EPR     Insulation Class:         MV
                +/-  Impedance: 0.0805 + J  0.0484  Ohms/1000 ft     0.00039 + J 0.00023  PU
                Z0   Impedance: 0.1279 + J  0.1230  Ohms/1000 ft     0.00062 + J 0.00060  PU

 350-2-40-1     SWGR N2-WEST    MCC-B-WEST       2   4160   40.0  FEET     350     Copper
                Duct Material: Non-Magnetic     Insulation Type:        EPR     Insulation Class:         MV
                +/-  Impedance: 0.0368 + J  0.0328  Ohms/1000 ft      0.0043 + J  0.0038  PU
                Z0   Impedance: 0.0585 + J  0.0834  Ohms/1000 ft      0.0068 + J  0.0096  PU

 350-2-40-2     SWGR N1-EAST    MCC-A-EAST       2   4160   40.0  FEET     350     Copper
                Duct Material: Non-Magnetic     Insulation Type:        EPR     Insulation Class:         MV
                +/-  Impedance: 0.0368 + J  0.0328  Ohms/1000 ft      0.0043 + J  0.0038  PU
                Z0   Impedance: 0.0585 + J  0.0834  Ohms/1000 ft      0.0068 + J  0.0096  PU

 350-2-65-3     XFMR - N2 SEC   SWGR N2-WEST     2   4160   65.0  FEET     350     Copper
                Duct Material: Non-Magnetic     Insulation Type:        EPR     Insulation Class:         MV
                +/-  Impedance: 0.0368 + J  0.0328  Ohms/1000 ft      0.0069 + J  0.0062  PU
                Z0   Impedance: 0.0585 + J  0.0834  Ohms/1000 ft      0.0110 + J  0.0157  PU

 350-2-75-4     XFMR - N1 SEC   SWGR N1-EAST     2   4160   75.0  FEET     350     Copper
                Duct Material: Non-Magnetic     Insulation Type:        EPR     Insulation Class:         MV
                +/-  Impedance: 0.0368 + J  0.0328  Ohms/1000 ft      0.0080 + J  0.0071  PU
                Z0   Impedance: 0.0585 + J  0.0834  Ohms/1000 ft      0.0127 + J  0.0181  PU

 500-1-70-4     XFMR-B SEC      ATS-1 E          1    480   70.0  FEET     500     Copper
                Duct Material:     Magnetic     Insulation Type:        PVC     Insulation Class:       THHN
```

```
             +/-   Impedance: 0.0294 + J  0.0466  Ohms/1000 ft      0.8932 + J    1.42  PU
              Z0   Impedance: 0.0926 + J  0.1147  Ohms/1000 ft        2.81 + J    3.48  PU

500-1-70-5    XFMR-A SEC      ATS-1 N          1    480   70.0  FEET     500     Copper
              Duct Material:     Magnetic     Insulation Type:         PVC     Insulation Class:       THHN
              +/-  Impedance: 0.0294 + J  0.0466  Ohms/1000 ft      0.8932 + J    1.42  PU
              Z0   Impedance: 0.0926 + J  0.1147  Ohms/1000 ft        2.81 + J    3.48  PU
```


TRANSFORMER INPUT DATA

```
===============================================================================================
TRANSFORMER    PRIMARY RECORD      VOLTS   * SECONDARY RECORD    VOLTS   FULL-LOAD    NOMINAL
NAME           NO NAME             L-L      NO NAME              L-L     KVA          KVA
===============================================================================================
XFMR-A-EAST    XFMR-A PRI     D  4160.00   XFMR-A SEC     YG    480.00  225.00       225.00
               Pos. Seq. Z%:     1.95 + J   4.80    (Zpu   8.67 + j  21.33 )    Shell Type
               Zero Seq. Z%:     1.95 + J   4.80    (Sec   8.67 + j  21.33 Pri  Open)
               Taps  Pri. 0.000 %  Sec. 0.000 %  Phase Shift (Pri. Leading Sec.):  30.00 Deg.

XFMR-B-WEST    XFMR-B PRI     D  4160.00   XFMR-B SEC     YG    480.00  225.00       225.00
               Pos. Seq. Z%:     1.95 + J   4.80    (Zpu   8.67 + j  21.33 )    Shell Type
               Zero Seq. Z%:     1.95 + J   4.80    (Sec   8.67 + j  21.33 Pri  Open)
               Taps  Pri. 0.000 %  Sec. 0.000 %  Phase Shift (Pri. Leading Sec.):  30.00 Deg.

XFMR - N1-EAST XFMR - N1 PRI  YG 24900.0   XFMR - N1 SEC  YG   4160.00 4687.50      3750.00
               Pos. Seq. Z%:    0.566 + J   6.48    (Zpu  0.151 + j   1.73 )    Shell Type
               Zero Seq. Z%:    0.566 + J   6.48    (     Pri - Sec: 104.2 + j   1.73 )
               Taps  Pri. 0.000 %  Sec. 0.000 %  Phase Shift (Pri. Leading Sec.):  0.000 Deg.
Secondary Neutral Z:     6.00 + J  0.000 Ohms

XFMR - N2-WEST XFMR- N2 PRI   YG 24900.0   XFMR - N2 SEC  YG   4160.00 4687.50      3750.00
               Pos. Seq. Z%:    0.566 + J   6.48    (Zpu  0.151 + j   1.73 )    Shell Type
               Zero Seq. Z%:    0.566 + J   6.48    (     Pri - Sec: 104.2 + j   1.73 )
               Taps  Pri. 0.000 %  Sec. 0.000 %  Phase Shift (Pri. Leading Sec.):  0.000 Deg.
Secondary Neutral Z:     6.00 + J  0.000 Ohms
```


VFD INPUT DATA

INPUT DATA - NORMAL OPERATION

```
===================================================================================================================
 VFD            VFD FROM       VFD TO           VOLTS    RATING      --CONTRIBUTION% OF RATING--
-----BYPASS IMPEDANCE------
 NAME           NAME           NAME                                  THREE PHASE   LINE-G    X/R    Z1%
X1/R1     Z0%   X0/R0

===================================================================================================================
 VFD-P1         VFD P1 IN      VFD-P1 OUT        4160     600  LineSide:      0         0      8       0
 8       0     8
                                                           HP   LoadSide:      0         0      8   Bypass Z
Not Applicable
               Power Factor:   0.9  Efficiency:    0.9  Line Reactor:     0%   Sevice Factor:    1   NOT in
Bypass Mode

*******************************************************************************************************************
***
```

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GENERATION CONTRIBUTION DATA

```
=====================================================================================
BUS            CONTRIBUTION    VOLTAGE
NAME           NAME              L-L     MVA      X"d    X/R
=====================================================================================
UTIL           UTILITY KONCOR  24900.0   89.15
                  Three Phase           Contribution:    2067.00 AMPS        2.01
                  Single Line to Ground Contribution:    1496.00 AMPS        2.01
                  Pos  Sequence Impedance (100 MVA Base)  0.4997 + J     1.00 PU
                  Zero Sequence Impedance (100 MVA Base)    1.07 + J     2.15 PU
```

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MOTOR CONTRIBUTION DATA

```
=====================================================================================
BUS            CONTRIBUTION      VOLTAGE    BASE                              Motor
NAME           NAME                L-L      kVA         X"d    X/R            Number
=====================================================================================
```

INPUT DATA - NORMAL OPERATION

PUMP1	PUMP #1-EAST	4160	554.30	0.1692	10.0	1.00
	Pos Sequence Impedance (100 MVA Base)			3.05 + j	30.52 PU	
PUMP 2	PUMP #2-EAST	4160	554.30	0.1692	10.0	1.00
	Pos Sequence Impedance (100 MVA Base)			3.05 + j	30.52 PU	
PUMP 4	PUMP #4-WEST	4160	746.93	0.1692	10.0	1.00
	Pos Sequence Impedance (100 MVA Base)			2.26 + j	22.65 PU	
PUMP 3	PUMP #3-WEST	4160	746.93	0.1692	10.0	1.00
	Pos Sequence Impedance (100 MVA Base)			2.26 + j	22.65 PU	

KAMAMA PUMP STATION
KATIA, TEXANA
EMERGENCY OPERATION

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INPUT DATA REPORT

ALL PU VALUES ARE EXPRESSED ON A 100 MVA BASE.

Mar 31, 2015 13:27:06 Page 2

FEEDER INPUT DATA

CABLE	FEEDER FROM	FEEDER TO	QTY	VOLTS	LENGTH	FEEDER

```
NAME          NAME            NAME           PH  L-L                      SIZE       TYPE

==============================================================================================================
===
1-1-110-3     MCC-B-WEST      PUMP 4          1   4160  110.0  FEET      1     Copper
              Duct Material: Non-Magnetic     Insulation Type:       EPR    Insulation Class:         MV
              +/-  Impedance: 0.1600 + J  0.0456  Ohms/1000 ft     0.1017 + J  0.0290  PU
              Z0   Impedance: 0.2543 + J  0.1160  Ohms/1000 ft     0.1616 + J  0.0737  PU

1-1-65-2      MCC-A-EAST      PUMP 2          1   4160   65.0  FEET      1     Copper
              Duct Material: Non-Magnetic     Insulation Type:       EPR    Insulation Class:         MV
              +/-  Impedance: 0.1600 + J  0.0456  Ohms/1000 ft     0.0601 + J  0.0171  PU
              Z0   Impedance: 0.2543 + J  0.1160  Ohms/1000 ft     0.0955 + J  0.0436  PU

1200A-5-1     SWGR GEN        SWGR N2-WEST    1   4160    5.0  FEET   1200     Copper
              Duct Material:       Busway     Insulation Type:     Epoxy    Insulation Class:    Class B
              +/-  Impedance: 0.0119 + J  0.0619  Ohms/1000 ft    0.00034 + J  0.0018  PU
              Z0   Impedance: 0.0710 + J  0.3314  Ohms/1000 ft     0.0021 + J  0.0096  PU

1200A-B-2     SWGR N2-WEST    SWGR N1-EAST    1   4160    5.0  FEET   1200     Copper
              Duct Material:       Busway     Insulation Type:     Epoxy    Insulation Class:    Class B
              +/-  Impedance: 0.0119 + J  0.0619  Ohms/1000 ft    0.00034 + J  0.0018  PU
              Z0   Impedance: 0.0710 + J  0.3314  Ohms/1000 ft     0.0021 + J  0.0096  PU

2-1-100-4     MCC-A-EAST      XFMR-A PRI      1   4160  100.0  FEET      2     Copper
              Duct Material: Non-Magnetic     Insulation Type:       EPR    Insulation Class:         MV
              +/-  Impedance: 0.2020 + J  0.0467  Ohms/1000 ft     0.1167 + J  0.0270  PU
              Z0   Impedance: 0.3211 + J  0.1188  Ohms/1000 ft     0.1855 + J  0.0686  PU

2-1-125-1     MCC-B-WEST     PUMP 3           1   4160  125.0  FEET      2     Copper
              Duct Material: Non-Magnetic     Insulation Type:       EPR    Insulation Class:         MV
              +/-  Impedance: 0.2020 + J  0.0467  Ohms/1000 ft     0.1459 + J  0.0337  PU
              Z0   Impedance: 0.3211 + J  0.1188  Ohms/1000 ft     0.2319 + J  0.0858  PU

2-1-20-5      MCC-A-EAST      VFD P1 IN       1   4160   20.0  FEET      2     Copper
              Duct Material: Non-Magnetic     Insulation Type:       EPR    Insulation Class:         MV
              +/-  Impedance: 0.2020 + J  0.0467  Ohms/1000 ft     0.0233 + J  0.0054  PU
              Z0   Impedance: 0.3211 + J  0.1188  Ohms/1000 ft     0.0371 + J  0.0137  PU

2-1-50-4      VFD-P1 OUT      PUMP1           1   4160   50.0  FEET      2     Copper
              Duct Material: Non-Magnetic     Insulation Type:       EPR    Insulation Class:         MV
              +/-  Impedance: 0.2020 + J  0.0467  Ohms/1000 ft     0.0584 + J  0.0135  PU
              Z0   Impedance: 0.3211 + J  0.1188  Ohms/1000 ft     0.0928 + J  0.0343  PU

2-1-85-1      MCC-B-WEST      XFMR-B PRI      1   4160   85.0  FEET      2     Copper
              Duct Material: Non-Magnetic     Insulation Type:       EPR    Insulation Class:         MV
              +/-  Impedance: 0.2020 + J  0.0467  Ohms/1000 ft     0.0992 + J  0.0229  PU
              Z0   Impedance: 0.3211 + J  0.1188  Ohms/1000 ft     0.1577 + J  0.0584  PU
```

FEEDER INPUT DATA

```
=================================================================================================
===
 CABLE          FEEDER FROM     FEEDER TO       QTY  VOLTS   LENGTH          FEEDER
 NAME           NAME            NAME            /PH  L-L                 SIZE       TYPE

=================================================================================================
===
 350-2-40-1     SWGR N2-WEST    MCC-B-WEST       2   4160   40.0  FEET     350     Copper
                Duct Material: Non-Magnetic     Insulation Type:        EPR     Insulation Class:         MV
                +/-  Impedance: 0.0368 + J  0.0328  Ohms/1000 ft     0.0043 + J  0.0038  PU
                Z0   Impedance: 0.0585 + J  0.0834  Ohms/1000 ft     0.0068 + J  0.0096  PU

 350-2-40-2     SWGR N1-EAST    MCC-A-EAST       2   4160   40.0  FEET     350     Copper
                Duct Material: Non-Magnetic     Insulation Type:        EPR     Insulation Class:         MV
                +/-  Impedance: 0.0368 + J  0.0328  Ohms/1000 ft     0.0043 + J  0.0038  PU
                Z0   Impedance: 0.0585 + J  0.0834  Ohms/1000 ft     0.0068 + J  0.0096  PU

 4/0-2-190-1    STANDBY GEN     SWGR GEN         2   4160  190.0  FEET     4/0     Copper
                Duct Material: Non-Magnetic     Insulation Type:        EPR     Insulation Class:         MV
                +/-  Impedance: 0.0633 + J  0.0332  Ohms/1000 ft     0.0347 + J  0.0182  PU
                Z0   Impedance: 0.1006 + J  0.0844  Ohms/1000 ft     0.0552 + J  0.0463  PU

 500-1-70-4     XFMR-B SEC      ATS-1 E          1    480   70.0  FEET     500     Copper
                Duct Material:     Magnetic     Insulation Type:        PVC     Insulation Class:       THHN
                +/-  Impedance: 0.0294 + J  0.0466  Ohms/1000 ft     0.8932 + J    1.42  PU
                Z0   Impedance: 0.0926 + J  0.1147  Ohms/1000 ft       2.81 + J    3.48  PU

 500-1-70-5     XFMR-A SEC      ATS-1 N          1    480   70.0  FEET     500     Copper
                Duct Material:     Magnetic     Insulation Type:        PVC     Insulation Class:       THHN
                +/-  Impedance: 0.0294 + J  0.0466  Ohms/1000 ft     0.8932 + J    1.42  PU
                Z0   Impedance: 0.0926 + J  0.1147  Ohms/1000 ft       2.81 + J    3.48  PU
```


TRANSFORMER INPUT DATA

```
                                            INPUT DATA - EMERGENCY OPERATION
===============================================================================================
 TRANSFORMER    PRIMARY RECORD      VOLTS   * SECONDARY RECORD    VOLTS   FULL-LOAD    NOMINAL
 NAME           NO NAME             L-L       NO NAME             L-L     KVA          KVA
===============================================================================================
 XFMR-A-EAST    XFMR-A PRI    D  4160.00   XFMR-A SEC     YG    480.00  225.00       225.00
                Pos. Seq. Z%:    1.95 + J   4.80    (Zpu   8.67 + j  21.33 )    Shell Type
                Zero Seq. Z%:    1.95 + J   4.80    (Sec   8.67 + j  21.33 Pri  Open)
                Taps  Pri. 0.000 %  Sec. 0.000 %  Phase Shift (Pri. Leading Sec.):  30.00 Deg.

 XFMR-B-WEST    XFMR-B PRI    D  4160.00   XFMR-B SEC     YG    480.00  225.00       225.00
                Pos. Seq. Z%:    1.95 + J   4.80    (Zpu   8.67 + j  21.33 )    Shell Type
                Zero Seq. Z%:    1.95 + J   4.80    (Sec   8.67 + j  21.33 Pri  Open)
                Taps  Pri. 0.000 %  Sec. 0.000 %  Phase Shift (Pri. Leading Sec.):  30.00 Deg.
```



```
                                                VFD  INPUT  DATA

==============================================================================================================
=================
 VFD           VFD FROM       VFD TO           VOLTS    RATING      --CONTRIBUTION% OF RATING--
-----BYPASS IMPEDANCE------
 NAME          NAME           NAME                                  THREE PHASE   LINE-G    X/R    Z1%
X1/R1     Z0%   X0/R0

==============================================================================================================
=================
 VFD-P1        VFD P1 IN      VFD-P1 OUT        4160     600  LineSide:      0         0      8       0
 8       0     8
                                                         HP   LoadSide:      0         0      8   Bypass Z
Not Applicable
               Power Factor:   0.9  Efficiency:    0.9  Line Reactor:     0%   Sevice Factor:    1   NOT in
Bypass Mode

*****************************************************************************************************************
***
```


GENERATION CONTRIBUTION DATA

INPUT DATA - EMERGENCY OPERATION

BUS NAME	CONTRIBUTION NAME	VOLTAGE L-L	MVA	X"d	X/R
STANDBY GEN	STANDBY GENERA	4160.00	2.81	0.1500	20.00

Neutral impedance 6.00 + J 0.00000 Ohms
KG: 0.9174 xdsat: 3.77 Excitation Limit: 1.30 Ik - ON
Pos Sequence Impedance (100 MVA Base) 0.2667 + J 5.33 PU

MOTOR CONTRIBUTION DATA

BUS NAME	CONTRIBUTION NAME	VOLTAGE L-L	BASE kVA	X"d	X/R	Motor Number
PUMP1	PUMP #1-EAST	4160	554.30	0.1692	10.0	1.00
	Pos Sequence Impedance (100 MVA Base) 3.05 + j 30.52 PU					
PUMP 2	PUMP #2-EAST	4160	554.30	0.1692	10.0	1.00
	Pos Sequence Impedance (100 MVA Base) 3.05 + j 30.52 PU					
PUMP 4	PUMP #4-WEST	4160	746.93	0.1692	10.0	1.00
	Pos Sequence Impedance (100 MVA Base) 2.26 + j 22.65 PU					
PUMP 3	PUMP #3-WEST	4160	746.93	0.1692	10.0	1.00
	Pos Sequence Impedance (100 MVA Base) 2.26 + j 22.65 PU					

Equipment Evaluation Report - All Buses

Bus	Manufacturer	Status	Type	Bus Voltage	Calc Isc kA	Dev Isc kA	Series Rating kA	Isc Rating%	Calc Mom kA	Dev Mom kA	Mom Rating%
25KV SWGR EXISTING	COOPER POWER	Pass	MV Switchgear	24900	2.30	12.00		19.17	2.43	20.00	12.16
480V MCC-CENTRAL	CUTLER-HAMMER	Pass	LV MCC	480	4.48	42.00		10.66			
COOPER iDP-210 SWGR	COOPER POWER	Pass	MV Switchgear	24900	2.30	12.00		19.17	2.43	20.00	12.16
MCC-A-EAST	CUTLER-HAMMER	Pass	MV E2 Starter	4160	5.49	50.00		10.98	6.75	80.00	8.44
MCC-B-WEST	CUTLER-HAMMER	Pass	MV E2 Starter	4160	6.18	50.00		12.35	7.64	80.00	9.55
SWGR N1-EAST	CUTLER-HAMMER	Pass	MV Switchgear	4160	5.50	33.18 (*N2)		16.57	6.77	58.00	11.67
SWGR N2-WEST	CUTLER-HAMMER	Pass	MV Switchgear	4160	6.18	33.18 (*N2)		18.63	7.66	58.00	13.21
(*N2) Dev Isc kA modified based on Max Rating Voltage and K Factor.											

Attachment III - Panel Evaluation-Normal Operation

Device/Bus Manufacturer	Status	Description	Voltage (V) Bus/Device	INT kA Calc/Dev/Series	Close-Latch kA Calc/Dev	Rating% Volt/INT/C-L	K Factor Ith 3P/SLG	PartingTime Speed Cycles
1200A-DISC-1	Pass	HVLCC	4160	5.49	6.75	83.20	0.00	0.0
MCC-A-EAST		25KA SYM,40 KA ASYM	5000	38.00	61.00	14.45		0.0
SQUARE D		1200A				11.07		Symm
1200A-DISC-2	Pass	HVLCC	4160	6.18	7.64	83.20	0.00	0.0
MCC-B-WEST		25KA SYM,40 KA ASYM	5000	38.00	61.00	16.25		0.0
SQUARE D		1200A				12.53		Symm
1200A-VCP-W-D1-EAST	Pass	VCP-W	4160	5.50	6.77	87.39	1.24	3.0
SWGR N1-EAST		600-3000A	4760	33.18 (*N2)	46.40	16.57		5.0
CUTLER-HAMMER		50 VCP-W-250				14.59		Symm
1200A-VCP-W-D2-WEST	Pass	VCP-W	4160	6.18	7.66	87.39	1.24	3.0
SWGR N2-WEST		600-3000A	4760	33.18 (*N2)	46.40	18.63		5.0
CUTLER-HAMMER		50 VCP-W-250				16.51		Symm
1200A-VCP-W-N1	Pass	VCP-W	4160	5.50	6.77	87.39	1.24	3.0
SWGR N1-EAST		600-3000A	4760	33.18 (*N2)	46.40	16.57		5.0
CUTLER-HAMMER		50 VCP-W-250				14.59		Symm
1200A-VCP-W-N2	Pass	VCP-W	4160	6.18	7.66	87.39	1.24	3.0
SWGR N2-WEST		600-3000A	4760	33.18 (*N2)	46.40	18.63		5.0
CUTLER-HAMMER		50 VCP-W-250				16.51		Symm
125E-CS3 FUSE	Pass	CS-3, 5.5kV E-Rated	4160	5.47	6.66	75.64		
VFD P1 IN		10E-450E	5500	63.00	100.00	8.68		
GOULD SHAWMUT		CS-3, 125E				6.66		Symm
400E FUSE-2	Pass	CS-3, 5.5kV E-Rated	4160	6.18	7.64	75.64		
MCC-B-WEST		10E-450E	5500	63.00	100.00	9.80		
GOULD SHAWMUT		CS-3, 400E				7.64		Symm

Device/Bus Manufacturer	Status	Description	Voltage (V) Bus/Device	INT kA Calc/Dev/Series	Close-Latch kA Calc/Dev	Rating% Volt/INT/C-L	K Factor Ith 3P/SLG	PartingTime Speed Cycles
400E-FUSE-1	Pass	CS-3, 5.5kV E-Rated	4160	5.49	6.75	75.64		
MCC-A-EAST		10E-450E	5500	63.00	100.00	8.72		
GOULD SHAWMUT		CS-3, 400E				6.75		Symm
CS3-40E-FUSE-1	Pass	CS-3, 5.5kV E-Rated	4160	5.49	6.75	75.64		
MCC-A-EAST		10E-450E	5500	63.00	100.00	8.72		
GOULD SHAWMUT		CS-3, 40E				6.75		Symm
CS3-40E-FUSE-2	Pass	CS-3, 5.5kV E-Rated	4160	6.18	7.64	75.64		
MCC-B-WEST		10E-450E	5500	63.00	100.00	9.80		
GOULD SHAWMUT		CS-3, 40E				7.64		Symm
EJ2-6R FUSE-1	Pass	9F60 EJ-2, 2.54 & 5.08kV R-Rated	4160	5.49	6.75	81.89		
MCC-A-EAST		2R-36R	5080	50.00	80.00	10.98		
GE		EJ-2, 6R				8.44		Symm
EJ2-6R FUSE-2	Pass	9F60 EJ-2, 2.54 & 5.08kV R-Rated	4160	5.49	6.75	81.89		
MCC-A-EAST		2R-36R	5080	50.00	80.00	10.98		
GE		EJ-2, 6R				8.44		Symm
EJ2-9R FUSE-5	Pass	9F60 EJ-2, 2.54 & 5.08kV R-Rated	4160	6.18	7.64	81.89		
MCC-B-WEST		2R-36R	5080	50.00	80.00	12.35		
GE		EJ-2, 9R				9.55		Symm
EJ2-9R FUSE-6	Pass	9F60 EJ-2, 2.54 & 5.08kV R-Rated	4160	6.18	7.64	81.89		
MCC-B-WEST		2R-36R	5080	50.00	80.00	12.35		
GE		EJ-2, 9R				9.55		Symm
TXU-ST1	Pass	Form 4C/A, PWVE	24900	2.30	2.43	100.00	1.00	3.0
UTIL		Phase, 101-202	24900	10.20	13.58	22.56		5.0

Device/Bus Manufacturer	Status	Description	Voltage (V) Bus/Device	INT kA Calc/Dev/Series	Close-Latch kA Calc/Dev	Rating% Volt/INT/C-L	K Factor Ith 3P/SLG	PartingTime Speed Cycles
COOPER		PWVE				17.91		Symm
TXU-ST2	Pass	Form 4C/A, PWVE	24900	2.30	2.43	100.00	1.00	3.0
UTIL		Phase, 101-202	24900	6.00	7.99	38.34		5.0
COOPER		PWVE				30.45		Symm
(*N2) Dev Isc kA modified based on Max Rating Voltage and K Factor.								

Equipment Evaluation Report - All Buses

Bus	Manufacturer	Status	Type	Bus Voltage	Calc Isc kA	Dev Isc kA	Series Rating kA	Isc Rating%	Calc Mom kA	Dev Mom kA	Mom Rating%
480V MCC-CENTRAL	CUTLER-HAMMER	Pass	LV MCC	480	4.42	42.00		10.52			
MCC-A-EAST	CUTLER-HAMMER	Pass	MV E2 Starter	4160	4.25	50.00		8.50	6.36	80.00	7.95
MCC-B-WEST	CUTLER-HAMMER	Pass	MV E2 Starter	4160	4.25	50.00		8.51	6.37	80.00	7.96
SWGR GEN	CUTLER-HAMMER	Pass	MV Switchgear	4160	4.26	33.18 (*N2)		12.83	6.38	58.00	11.00
SWGR N1-EAST	CUTLER-HAMMER	Pass	MV Switchgear	4160	4.25	33.18 (*N2)		12.82	6.38	58.00	10.99
SWGR N2-WEST	CUTLER-HAMMER	Pass	MV Switchgear	4160	4.26	33.18 (*N2)		12.83	6.38	58.00	11.00
(*N2) Dev Isc kA modified based on Max Rating Voltage and K Factor.											

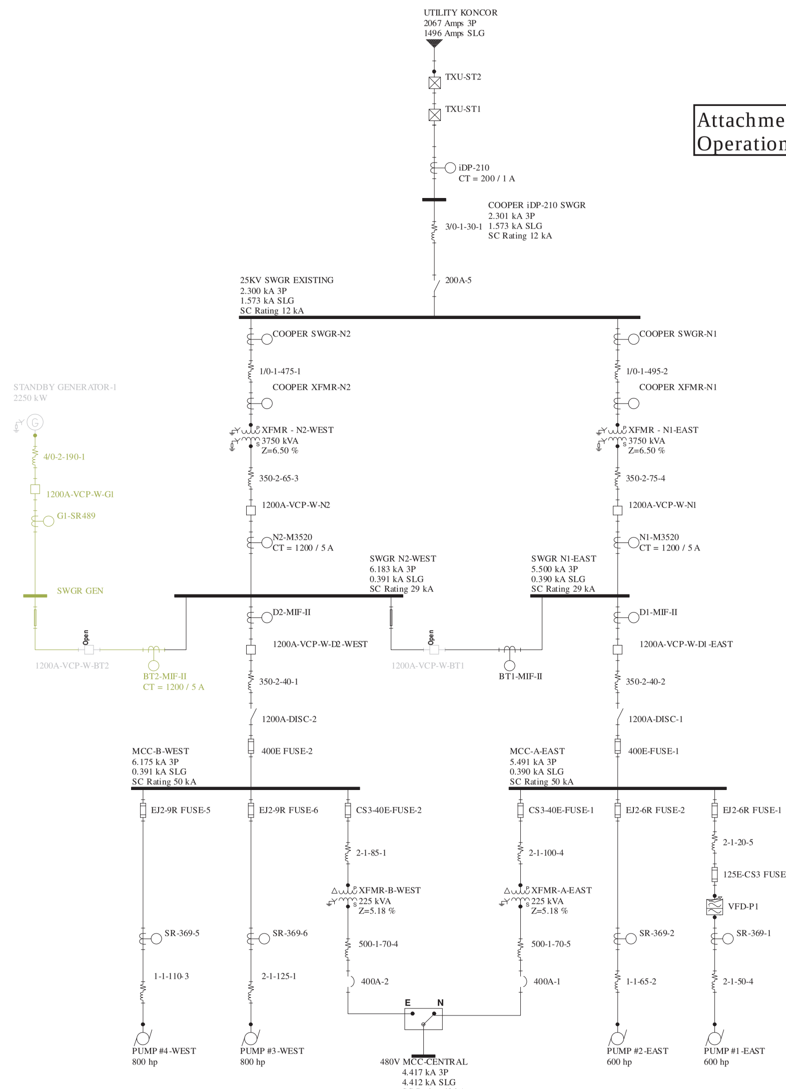
Attachment V - Panel Evaluation-Emergency Operation

Device/Bus Manufacturer	Status	Description	Voltage (V) Bus/Device	INT kA Calc/Dev/Series	Close-Latch kA Calc/Dev	Rating% Volt/INT/C-L	K Factor Ith 3P/SLG	PartingTime Speed Cycles
1200A-DISC-1	Pass	HVLCC	4160	4.25	6.36	83.20	0.00	0.0
MCC-A-EAST		25KA SYM,40 KA ASYM	5000	38.00	61.00	11.18		0.0
SQUARE D		1200A				10.42		Symm
1200A-DISC-2	Pass	HVLCC	4160	4.25	6.37	83.20	0.00	0.0
MCC-B-WEST		25KA SYM,40 KA ASYM	5000	38.00	61.00	11.19		0.0
SQUARE D		1200A				10.44		Symm
1200A-VCP-W-BT1	Pass	VCP-W	4160	4.25	6.38	87.39	1.24	3.0
SWGR N1-EAST		600-3000A	4760	33.18 (*N2)	46.40	12.82		5.0
CUTLER-HAMMER		50 VCP-W-250				13.74		Symm
1200A-VCP-W-BT2	Pass	VCP-W	4160	4.26	6.38	87.39	1.24	3.0
SWGR N2-WEST		600-3000A	4760	33.18 (*N2)	46.40	12.83		5.0
CUTLER-HAMMER		50 VCP-W-250				13.75		Symm
1200A-VCP-W-D1-EAST	Pass	VCP-W	4160	4.25	6.38	87.39	1.24	3.0
SWGR N1-EAST		600-3000A	4760	33.18 (*N2)	46.40	12.82		5.0
CUTLER-HAMMER		50 VCP-W-250				13.74		Symm
1200A-VCP-W-D2-WEST	Pass	VCP-W	4160	4.26	6.38	87.39	1.24	3.0
SWGR N2-WEST		600-3000A	4760	33.18 (*N2)	46.40	12.83		5.0
CUTLER-HAMMER		50 VCP-W-250				13.75		Symm
1200A-VCP-W-G1	Pass	VCP-W	4160	4.26	6.38	87.39	1.24	3.0
SWGR GEN		600-3000A	4760	33.18 (*N2)	46.40	12.83		5.0
CUTLER-HAMMER		50 VCP-W-250				13.75		Symm
125E-CS3 FUSE	Pass	CS-3, 5.5kV E-Rated	4160	4.24	6.27	75.64		
VFD P1 IN		10E-450E	5500	63.00	100.00	6.73		
GOULD SHAWMUT		CS-3, 125E				6.27		Symm

Device/Bus Manufacturer	Status	Description	Voltage (V) Bus/Device	INT kA Calc/Dev/Series	Close-Latch kA Calc/Dev	Rating% Volt/INT/C-L	K Factor Ith 3P/SLG	PartingTime Speed Cycles
400E FUSE-2	Pass	CS-3, 5.5kV E-Rated	4160	4.25	6.37	75.64		
MCC-B-WEST		10E-450E	5500	63.00	100.00	6.75		
GOULD SHAWMUT		CS-3, 400E				6.37		Symm
400E-FUSE-1	Pass	CS-3, 5.5kV E-Rated	4160	4.25	6.36	75.64		
MCC-A-EAST		10E-450E	5500	63.00	100.00	6.75		
GOULD SHAWMUT		CS-3, 400E				6.36		Symm
CS3-40E-FUSE-1	Pass	CS-3, 5.5kV E-Rated	4160	4.25	6.36	75.64		
MCC-A-EAST		10E-450E	5500	63.00	100.00	6.75		
GOULD SHAWMUT		CS-3, 40E				6.36		Symm
CS3-40E-FUSE-2	Pass	CS-3, 5.5kV E-Rated	4160	4.25	6.37	75.64		
MCC-B-WEST		10E-450E	5500	63.00	100.00	6.75		
GOULD SHAWMUT		CS-3, 40E				6.37		Symm
EJ2-6R FUSE-1	Pass	9F60 EJ-2, 2.54 & 5.08kV R-Rated	4160	4.25	6.36	81.89		
MCC-A-EAST		2R-36R	5080	50.00	80.00	8.50		
GE		EJ-2, 6R				7.95		Symm
EJ2-6R FUSE-2	Pass	9F60 EJ-2, 2.54 & 5.08kV R-Rated	4160	4.25	6.36	81.89		
MCC-A-EAST		2R-36R	5080	50.00	80.00	8.50		
GE		EJ-2, 6R				7.95		Symm
EJ2-9R FUSE-5	Pass	9F60 EJ-2, 2.54 & 5.08kV R-Rated	4160	4.25	6.37	81.89		
MCC-B-WEST		2R-36R	5080	50.00	80.00	8.51		
GE		EJ-2, 9R				7.96		Symm
EJ2-9R FUSE-6	Pass	9F60 EJ-2, 2.54 & 5.08kV R-Rated	4160	4.25	6.37	81.89		
MCC-B-WEST		2R-36R	5080	50.00	80.00	8.51		

	Device/Bus Manufacturer	Status	Description	Voltage (V) Bus/Device	INT kA Calc/Dev/Series	Close-Latch kA Calc/Dev	Rating% Volt/INT/C-L	K Factor Ith 3P/SLG	PartingTime Speed Cycles
	GE		EJ-2, 9R				7.96		Symm
	(*N2) Dev Isc kA modified based on Max Rating Voltage and K Factor.								

Attachment VII - Short-Circuit Study One-Line Diagram – Normal Operation

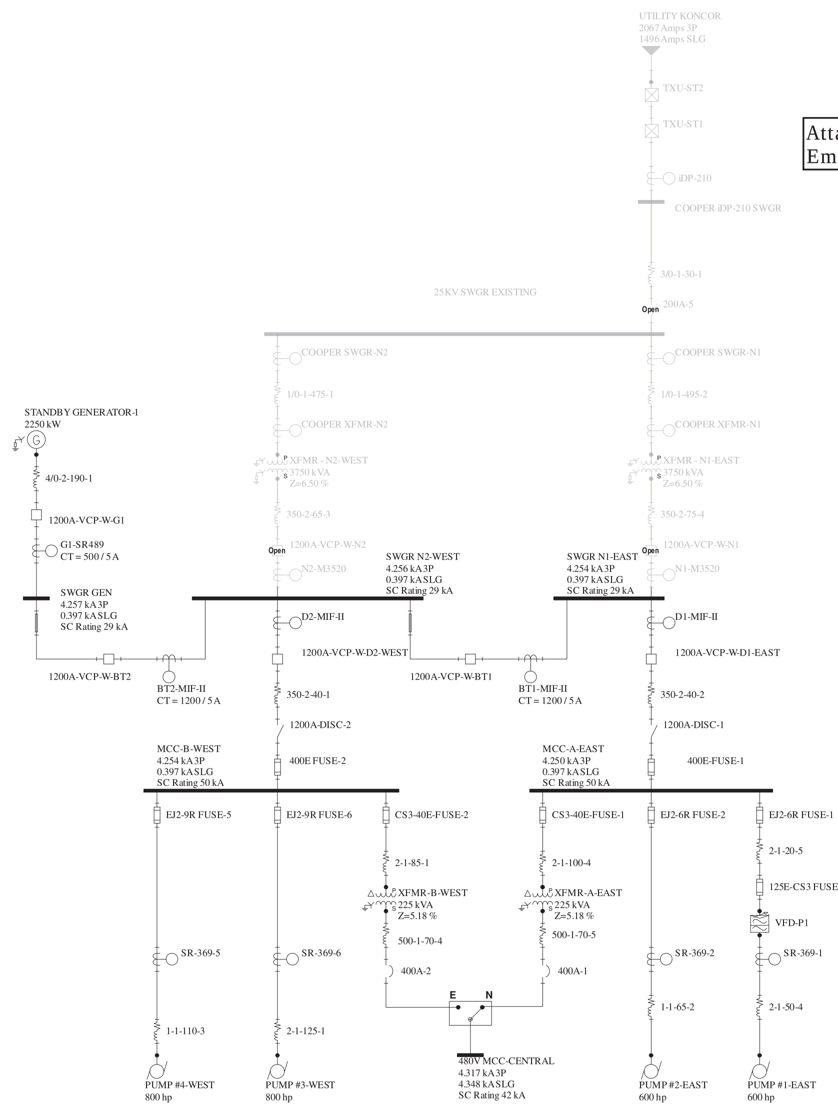


REV. 01

SHORT CIRCUIT STUDY ONELINE DIAGRAM - MAIN
KAMAMA PUMP STATION
KATIA, TEXANA

NORMAL OPERATION

Attachment VIII - Short-Circuit Study One-Line Diagram – Emergency Operation



REV. 01

SHORT CIRCUIT STUDY ONELINE DIAGRAM – MAIN
KAMAMA PUMP STATION
KATIA, TEXANA

EMERGENCY OPERATION

Project: KAMAMA PUMPSTATION UPGRADE
KAMAMA PUMP STATION
KATIA, TEXANA
NORMAL OPERATION

ANSI Complete Fault Report

A_FAULT Settings

Fault Type	3 Phase+Unbalanced	**LV Duty**	Yes	**Int Duty**	Yes
Faulted Bus	All Buses	**LV Report**	Complete	**Int Report**	Complete
Include Tap	No	**Mom Duty**	Yes	**Solution Method**	E/Z
Pre-fault Voltage	1.0000	**Mom Report**	Complete	**NACD Option**	Interpolated

Low Voltage 3 Phase and Unbalanced

Fault Location Bus Name	Bus Voltage		Fault Duty kA	Fault Duty MVA	X/R	-----Asym kA----- Max RMS	Avg RMS	Sequence Impedance pu		Equivalent R	+jX
25KV SWGR EXISTING	24,900	3 Phase:	2.30	99.2	2.75	2.52	2.41	Z1:	1.01	2.57	5.70
		SLG:	1.57	39.2	2.29	1.67	---	Z2:	1.01	---	---
		LL:	1.99	49.6	---	---	---	Z0:	2.41	---	---
LLG Gnd Return kA:	1.195	LLG:	2.10	52.2	---	---	---				
480V MCC-CENTRAL	480	3 Phase:	4.42	3.7	2.49	4.76	4.59	Z1:	27.23	0.02	0.06
		SLG:	4.41	2.1	2.37	4.71	---	Z2:	27.23	---	---
		LL:	3.82	1.8	---	---	---	Z0:	27.34	---	---
LLG Gnd Return kA:	4.406	LLG:	4.48	2.1	---	---	---				
COOPER iDP-210 SWGR	24,900	3 Phase:	2.30	99.2	2.75	2.52	2.41	Z1:	1.01	2.57	5.70
		SLG:	1.57	39.2	2.29	1.67	---	Z2:	1.01	---	---
		LL:	1.99	49.6	---	---	---	Z0:	2.41	---	---
LLG Gnd Return kA:	1.195	LLG:	2.10	52.2	---	---	---				
MCC-A-EAST	4,160	3 Phase:	5.49	39.6	5.35	6.98	6.26	Z1:	2.53	0.09	0.43
		SLG:	0.39	1.6	0.08	0.39	---	Z2:	2.53	---	---
		LL:	4.76	19.8	---	---	---	Z0:	105.42	---	---
LLG Gnd Return kA:	0.197	LLG:	4.85	20.2	---	---	---				
MCC-B-WEST	4,160	3 Phase:	6.18	44.5	5.45	7.89	7.06	Z1:	2.25	0.08	0.38
		SLG:	0.39	1.6	0.08	0.39	---	Z2:	2.25	---	---
		LL:	5.35	22.2	---	---	---	Z0:	105.42	---	---
LLG Gnd Return kA:	0.197	LLG:	5.44	22.6	---	---	---				
SWGR N1-EAST	4,160	3 Phase:	5.50	39.6	5.38	7.00	6.28	Z1:	2.52	0.09	0.43
		SLG:	0.39	1.6	0.08	0.39	---	Z2:	2.52	---	---
		LL:	4.76	19.8	---	---	---	Z0:	105.41	---	---
LLG Gnd Return kA:	0.197	LLG:	4.86	20.2	---	---	---				

Low Voltage 3 Phase and Unbalanced

Fault Location Bus Name	Bus Voltage		Fault Duty kA	Fault Duty MVA	X/R	-----Asym kA----- Max RMS	Avg RMS	Sequence Impedance pu		Equivalent R	+jX
SWGR N2-WEST	4,160	3 Phase:	6.18	44.6	5.46	7.90	7.07	Z1:	2.24	0.08	0.38
		SLG:	0.39	1.6	0.08	0.39	---	Z2:	2.24	---	---
		LL:	5.35	22.3	---	---	---	Z0:	105.41	---	---
LLG Gnd Return kA:	0.197	LLG:	5.45	22.7	---	---	---				

Momentary 3 Phase

Fault Location Bus Name	Bus Voltage	-----Sym Fault Duty----- kA	MVA	X/R	---------Mom kA--------- Sym*1.6	Based on X/R	--------Crest kA-------- Sym*2.7	Based on X/R	Equivalent R	+jX
25KV SWGR EXISTING	24,900	2.264	97.66	2.65	3.623	2.470	6.114	4.180	2.64	5.77
COOPER iDP-210 SWGR	24,900	2.265	97.69	2.65	3.624	2.470	6.116	4.180	2.64	5.77
MCC-A-EAST	4,160	5.397	38.89	5.19	8.635	6.820	14.572	11.800	0.10	0.43
MCC-B-WEST	4,160	5.965	42.98	5.28	9.544	7.560	16.105	13.090	0.08	0.39
SWGR N1-EAST	4,160	5.406	38.95	5.21	8.649	6.840	14.595	11.830	0.10	0.43
SWGR N2-WEST	4,160	5.973	43.04	5.29	9.557	7.580	16.127	13.110	0.08	0.39

Momentary Unbalanced

Fault Location Bus Name	Bus Voltage		---Sym Fault Duty--- kA	MVA	X/R	--Mom. Fault Duty-- kA*1.6	Based on X/R	Sequence Impedance pu	
25KV SWGR EXISTING	24,900	3 Phase:	2.264	97.66	2.65	3.623	2.470	Z1:	1.02
		SLG:	1.562	38.88	2.26	2.499	1.660	Z2:	1.02
		LL:	1.961	48.83	---	---	---	Z0:	2.41
LLG Gnd Return kA:	1.19	LLG:	2.065	51.41	---	---	---		
COOPER iDP-210 SWGR	24,900	3 Phase:	2.265	97.69	2.65	3.624	2.470	Z1:	1.02
		SLG:	1.562	38.90	2.26	2.499	1.660	Z2:	1.02
		LL:	1.962	48.85	---	---	---	Z0:	2.41
LLG Gnd Return kA:	1.19	LLG:	2.066	51.43	---	---	---		
MCC-A-EAST	4,160	3 Phase:	5.397	38.89	5.19	8.635	6.820	Z1:	2.57
		SLG:	0.390	1.62	0.08	0.624	0.390	Z2:	2.57
		LL:	4.674	19.44	---	---	---	Z0:	105.42
LLG Gnd Return kA:	0.20	LLG:	4.769	19.84	---	---	---		
MCC-B-WEST	4,160	3 Phase:	5.965	42.98	5.28	9.544	7.560	Z1:	2.33
		SLG:	0.390	1.62	0.08	0.625	0.390	Z2:	2.33
		LL:	5.166	21.49	---	---	---	Z0:	105.42
LLG Gnd Return kA:	0.20	LLG:	5.261	21.89	---	---	---		
SWGR N1-EAST	4,160	3 Phase:	5.406	38.95	5.21	8.649	6.840	Z1:	2.57
		SLG:	0.390	1.62	0.08	0.624	0.390	Z2:	2.57
		LL:	4.681	19.47	---	---	---	Z0:	105.41
LLG Gnd Return kA:	0.20	LLG:	4.776	19.87	---	---	---		
SWGR N2-WEST	4,160	3 Phase:	5.973	43.04	5.29	9.557	7.580	Z1:	2.32
		SLG:	0.390	1.62	0.08	0.625	0.390	Z2:	2.32
		LL:	5.173	21.52	---	---	---	Z0:	105.41
LLG Gnd Return kA:	0.20	LLG:	5.268	21.92	---	---	---		

Interrupting 3 Phase and Unbalanced

Fault Location Bus Name	Bus Voltage		-----Init Sym Fault----- kA	X/R	Equivalent R	+jX	Seq. Imp. pu		-------Interrupting Fault kA----- 2 cyc.	3 cyc.	5 cyc.	8 cyc.
25KV SWGR	24,900	3 Phase:	2.15	2.30	2.89	6.03	Z1: 1.08	3Ph.Sym:	2.15	2.15	2.15	2.15
EXISTING		SLG:	1.52	2.14	---	---	Z2: 1.08	Tot:	2.19	2.15	2.15	2.15
NACD:	0.96	LL:	1.86	---	---	---	Z0: 2.41	SLG Sym:	1.52	1.52	1.52	1.52
LLG Gnd Return kA:	1.180	LLG:	1.96	---	---	---		Tot:	1.55	1.52	1.52	1.52
COOPER iDP-210	24,900	3 Phase:	2.15	2.30	2.89	6.03	Z1: 1.08	3Ph.Sym:	2.15	2.15	2.15	2.15
SWGR		SLG:	1.52	2.14	---	---	Z2: 1.08	Tot:	2.19	2.15	2.15	2.15
NACD:	0.96	LL:	1.86	---	---	---	Z0: 2.41	SLG Sym:	1.52	1.52	1.52	1.52
LLG Gnd Return kA:	1.181	LLG:	1.96	---	---	---		Tot:	1.55	1.52	1.52	1.52
MCC-A-EAST	4,160	3 Phase:	5.11	4.59	0.11	0.46	Z1: 2.72	3Ph.Sym:	5.11	5.11	5.11	5.11
		SLG:	0.39	0.09	---	---	Z2: 2.72	Tot:	5.34	5.11	5.11	5.11
NACD:	0.94	LL:	4.42	---	---	---	Z0: 105.4	SLG Sym:	0.39	0.39	0.39	0.39
LLG Gnd Return kA:	0.197	LLG:	4.52	---	---	---		Tot:	0.39	0.39	0.39	0.39
MCC-B-WEST	4,160	3 Phase:	5.33	4.64	0.10	0.44	Z1: 2.60	3Ph.Sym:	5.33	5.33	5.33	5.33
		SLG:	0.39	0.08	---	---	Z2: 2.60	Tot:	5.57	5.33	5.33	5.33
NACD:	0.91	LL:	4.62	---	---	---	Z0: 105.4	SLG Sym:	0.39	0.39	0.39	0.39
LLG Gnd Return kA:	0.197	LLG:	4.71	---	---	---		Tot:	0.39	0.39	0.39	0.39
SWGR N1-EAST	4,160	3 Phase:	5.12	4.62	0.11	0.46	Z1: 2.71	3Ph.Sym:	5.12	5.12	5.12	5.12
		SLG:	0.39	0.09	---	---	Z2: 2.71	Tot:	5.35	5.12	5.12	5.12
NACD:	0.94	LL:	4.43	---	---	---	Z0: 105.4	SLG Sym:	0.39	0.39	0.39	0.39
LLG Gnd Return kA:	0.197	LLG:	4.53	---	---	---		Tot:	0.39	0.39	0.39	0.39
SWGR N2-WEST	4,160	3 Phase:	5.34	4.66	0.10	0.44	Z1: 2.60	3Ph.Sym:	5.34	5.34	5.34	5.34
		SLG:	0.39	0.08	---	---	Z2: 2.60	Tot:	5.58	5.34	5.34	5.34
NACD:	0.91	LL:	4.63	---	---	---	Z0: 105.4	SLG Sym:	0.39	0.39	0.39	0.39
LLG Gnd Return kA:	0.197	LLG:	4.72	---	---	---		Tot:	0.39	0.39	0.39	0.39

Project: KAMAMA PUMPSTATION UPGRADE
KAMAMA PUMP STATION
KATIA, TEXANA
EMERGENCY OPERATION

ANSI Complete Fault Report

A_FAULT Settings

Fault Type	3 Phase+Unbalanced	**LV Duty**	Yes	**Int Duty**	Yes
Faulted Bus	All Buses	**LV Report**	Complete	**Int Report**	Complete
Include Tap	No	**Mom Duty**	Yes	**Solution Method**	E/Z
Pre-fault Voltage	1.0000	**Mom Report**	Complete	**NACD Option**	Interpolated

Low Voltage 3 Phase and Unbalanced

Fault Location Bus Name	Bus Voltage		Fault Duty kA	Fault Duty MVA	X/R	-----Asym kA----- Max RMS	Avg RMS	Sequence Impedance pu		Equivalent R	+jX
480V MCC-CENTRAL	480	3 Phase:	4.32	3.6	2.63	4.70	4.51	Z1:	27.86	0.02	0.06
		SLG:	4.35	2.1	2.46	4.67	---	Z2:	27.83	---	---
		LL:	3.74	1.8	---	---	---	Z0:	27.34	---	---
LLG Gnd Return kA:	4.372	LLG:	4.42	2.1	---	---	---				
MCC-A-EAST	4,160	3 Phase:	4.25	30.6	14.29	6.43	5.40	Z1:	3.27	0.04	0.56
		SLG:	0.40	1.7	0.07	0.40	---	Z2:	3.24	---	---
		LL:	3.70	15.4	---	---	---	Z0:	104.10	---	---
LLG Gnd Return kA:	0.199	LLG:	3.80	15.8	---	---	---				
MCC-B-WEST	4,160	3 Phase:	4.25	30.7	14.36	6.44	5.41	Z1:	3.26	0.04	0.56
		SLG:	0.40	1.7	0.07	0.40	---	Z2:	3.23	---	---
		LL:	3.70	15.4	---	---	---	Z0:	104.10	---	---
LLG Gnd Return kA:	0.199	LLG:	3.80	15.8	---	---	---				
SWGR GEN	4,160	3 Phase:	4.26	30.7	14.53	6.45	5.42	Z1:	3.26	0.04	0.56
		SLG:	0.40	1.7	0.07	0.40	---	Z2:	3.23	---	---
		LL:	3.70	15.4	---	---	---	Z0:	104.09	---	---
LLG Gnd Return kA:	0.199	LLG:	3.80	15.8	---	---	---				
SWGR N1-EAST	4,160	3 Phase:	4.25	30.7	14.51	6.45	5.41	Z1:	3.26	0.04	0.56
		SLG:	0.40	1.7	0.07	0.40	---	Z2:	3.23	---	---
		LL:	3.70	15.4	---	---	---	Z0:	104.09	---	---
LLG Gnd Return kA:	0.199	LLG:	3.80	15.8	---	---	---				
SWGR N2-WEST	4,160	3 Phase:	4.26	30.7	14.52	6.45	5.42	Z1:	3.26	0.04	0.56
		SLG:	0.40	1.7	0.07	0.40	---	Z2:	3.23	---	---
		LL:	3.70	15.4	---	---	---	Z0:	104.09	---	---
LLG Gnd Return kA:	0.199	LLG:	3.80	15.8	---	---	---				

Attachment X - Short-Circuit Study Computer Output Report – Emergency Operation

Momentary 3 Phase

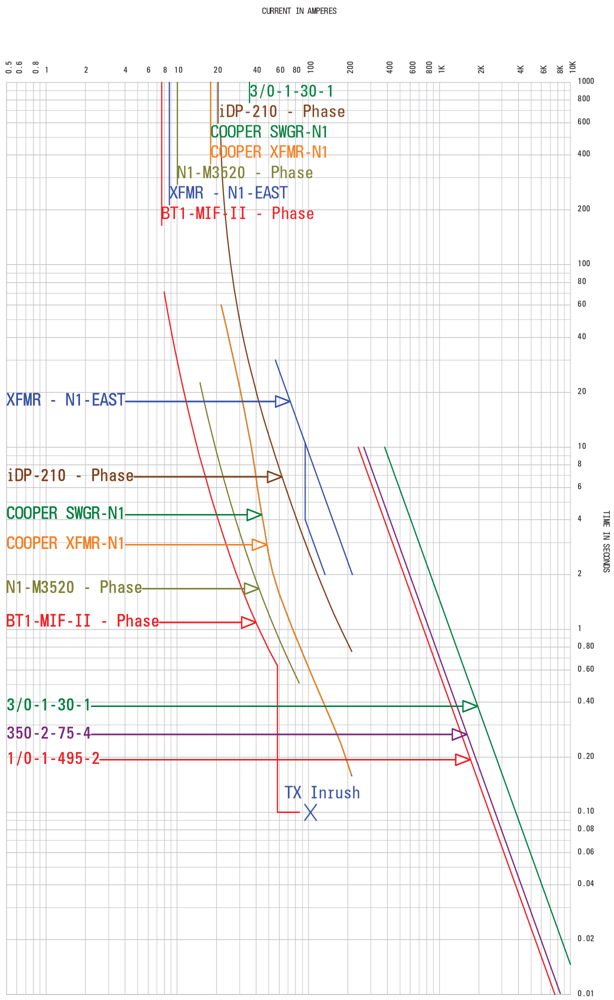
Fault Location Bus Name	Bus Voltage	-----Sym Fault Duty----- kA	MVA	X/R	---------Mom kA--------- Sym*1.6	Based on X/R	--------Crest kA-------- Sym*2.7	Based on X/R	Equivalent R	+jX
MCC-A-EAST	4,160	3.973	28.63	14.66	6.357	6.030	10.728	10.150	0.04	0.60
MCC-B-WEST	4,160	3.976	28.65	14.73	6.362	6.040	10.736	10.170	0.04	0.60
SWGR GEN	4,160	3.979	28.67	14.91	6.367	6.050	10.744	10.190	0.04	0.60
SWGR N1-EAST	4,160	3.977	28.66	14.88	6.363	6.050	10.738	10.180	0.04	0.60
SWGR N2-WEST	4,160	3.979	28.67	14.90	6.366	6.050	10.742	10.180	0.04	0.60

Momentary Unbalanced

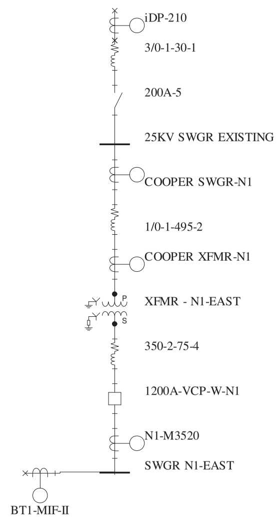
Fault Location Bus Name	Bus Voltage		---Sym Fault Duty--- kA	MVA	X/R	--Mom. Fault Duty-- kA*1.6	Based on X/R	Sequence Impedance pu	
MCC-A-EAST	4,160	3 Phase:	3.973	28.63	14.66	6.357	6.030	Z1:	3.49
		SLG:	0.397	1.65	0.07	0.635	0.400	Z2:	3.46
		LL:	3.457	14.38	---	---	---	Z0:	104.10
LLG Gnd Return kA:	0.20	LLG:	3.556	14.79	---	---	---		
MCC-B-WEST	4,160	3 Phase:	3.976	28.65	14.73	6.362	6.040	Z1:	3.49
		SLG:	0.397	1.65	0.07	0.635	0.400	Z2:	3.46
		LL:	3.459	14.39	---	---	---	Z0:	104.10
LLG Gnd Return kA:	0.20	LLG:	3.558	14.80	---	---	---		
SWGR GEN	4,160	3 Phase:	3.979	28.67	14.91	6.367	6.050	Z1:	3.49
		SLG:	0.397	1.65	0.07	0.635	0.400	Z2:	3.46
		LL:	3.462	14.40	---	---	---	Z0:	104.09
LLG Gnd Return kA:	0.20	LLG:	3.561	14.81	---	---	---		
SWGR N1-EAST	4,160	3 Phase:	3.977	28.66	14.88	6.363	6.050	Z1:	3.49
		SLG:	0.397	1.65	0.07	0.635	0.400	Z2:	3.46
		LL:	3.460	14.39	---	---	---	Z0:	104.09
LLG Gnd Return kA:	0.20	LLG:	3.559	14.80	---	---	---		
SWGR N2-WEST	4,160	3 Phase:	3.979	28.67	14.90	6.366	6.050	Z1:	3.49
		SLG:	0.397	1.65	0.07	0.635	0.400	Z2:	3.46
		LL:	3.461	14.40	---	---	---	Z0:	104.09
LLG Gnd Return kA:	0.20	LLG:	3.560	14.81	---	---	---		

Interrupting 3 Phase and Unbalanced

Fault Location Bus Name	Bus Voltage		-----Init Sym Fault----- kA	X/R	Equivalent R	+jX	Seq. Imp. pu		-------Interrupting Fault kA----- 2 cyc.	3 cyc.	5 cyc.	8 cyc.
MCC-A-EAST	4,160	3 Phase:	3.14	16.10	0.05	0.76	Z1: 4.42	3Ph.Sym:	3.14	3.14	3.14	3.14
		SLG:	0.40	0.09	---	---	Z2: 4.37	Tot:	4.21	3.57	3.21	3.14
NACD:	0.00	LL:	2.74	---	---	---	Z0: 104.1(	SLG Sym:	0.40	0.40	0.40	0.40
LLG Gnd Return kA:	0.198	LLG:	2.83	---	---	---		Tot:	0.40	0.40	0.40	0.40
MCC-B-WEST	4,160	3 Phase:	3.14	16.13	0.05	0.76	Z1: 4.42	3Ph.Sym:	3.14	3.14	3.14	3.14
		SLG:	0.40	0.09	---	---	Z2: 4.37	Tot:	4.22	3.58	3.21	3.14
NACD:	0.00	LL:	2.74	---	---	---	Z0: 104.1(	SLG Sym:	0.40	0.40	0.40	0.40
LLG Gnd Return kA:	0.198	LLG:	2.84	---	---	---		Tot:	0.40	0.40	0.40	0.40
SWGR GEN	4,160	3 Phase:	3.15	16.35	0.05	0.76	Z1: 4.41	3Ph.Sym:	3.15	3.15	3.15	3.15
		SLG:	0.40	0.09	---	---	Z2: 4.36	Tot:	4.23	3.59	3.22	3.15
NACD:	0.00	LL:	2.74	---	---	---	Z0: 104.0(	SLG Sym:	0.40	0.40	0.40	0.40
LLG Gnd Return kA:	0.199	LLG:	2.84	---	---	---		Tot:	0.40	0.40	0.40	0.40
SWGR N1-EAST	4,160	3 Phase:	3.14	16.32	0.05	0.76	Z1: 4.41	3Ph.Sym:	3.14	3.14	3.14	3.14
		SLG:	0.40	0.09	---	---	Z2: 4.36	Tot:	4.23	3.58	3.22	3.14
NACD:	0.00	LL:	2.74	---	---	---	Z0: 104.0(	SLG Sym:	0.40	0.40	0.40	0.40
LLG Gnd Return kA:	0.199	LLG:	2.84	---	---	---		Tot:	0.40	0.40	0.40	0.40
SWGR N2-WEST	4,160	3 Phase:	3.14	16.34	0.05	0.76	Z1: 4.41	3Ph.Sym:	3.14	3.14	3.14	3.14
		SLG:	0.40	0.09	---	---	Z2: 4.36	Tot:	4.23	3.59	3.22	3.14
NACD:	0.00	LL:	2.74	---	---	---	Z0: 104.0(	SLG Sym:	0.40	0.40	0.40	0.40
LLG Gnd Return kA:	0.199	LLG:	2.84	---	---	---		Tot:	0.40	0.40	0.40	0.40



CURRENT IN AMP x 10 @ 24900 VOLTS




```
Project Name:      KAMAMA PUMPSTATION UPGRADE(Base Project)
TCC Name:          TCC # 01 SWGR N1-EAST PROTECTION.tcc
Reference Voltage: 24900 V
Current Scale:     X 10^1
Fault Duty Option: Study Result - Bus Fault Current

-------------------------------------------------------------------------------
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-------------------------------------------------------------------------------

-------------------------------------------------------------------------------
Device Name:      iDP-210                                TCC Name:          TCC # 01 SWGR N1-EAST PROTECTION.tcc
Bus Name:         COOPER iDP-210 SWGR                    Bus Voltage:       24900.0V
Function Name:    Phase
Manufacturer:     COOPER
Description:      50/51
Type:             iDP-210                                Class Desc:        iDP-210
AIC Rating:       N/A                                    Fault Duty:        2150.8A
Current Rating:   200A / 1A                              Curve Multiplier: 1
Time Multiplier: 1                                       Time Adder:        0
Setting: 1) Pickup, (0.025 - 90A   1.025         (205A)  Test Points: @2.0X, 19.043s
         2) IEEE EI                2                                  @5.0X, 2.593s
                                                                      @10.0X, 0.813s

-------------------------------------------------------------------------------
Device Name:      COOPER SWGR-N1                         TCC Name:          TCC # 01 SWGR N1-EAST PROTECTION.tcc
Bus Name:         25KV SWGR EXISTING                     Bus Voltage:       24900.0V
Function Name:    Phase
Manufacturer:     COOPER
Description:      Phase Settings
Type:             VFI, Tri-Phase Control                 Class Desc:
AIC Rating:       N/A                                    Fault Duty:        2150.0A
Current Rating:   200A / 1A                              Curve Multiplier: 1
Time Multiplier: 1                                       Time Adder:        0
Setting: 1) Minimum Trip           180           (180A)  Test Points: @2.0X, 11.000s
         2) TF-Response                                               @5.0X, 0.747s
         3) INST                   15x          (2700A)               @10.0X, 0.230s
         4) INST-Delay             Fixed        (seconds)

-------------------------------------------------------------------------------
Device Name:      COOPER XFMR-N1                         TCC Name:          TCC # 01 SWGR N1-EAST PROTECTION.tcc
Bus Name:         XFMR - N1 PRI                          Bus Voltage:       24900.0V
Function Name:    Phase
Manufacturer:     COOPER
Description:      Phase Settings
Type:             VFI, Tri-Phase Control                 Class Desc:
AIC Rating:       N/A                                    Fault Duty:        2134.3A
Current Rating:   200A / 1A                              Curve Multiplier: 1
Time Multiplier: 1                                       Time Adder:        0
Setting: 1) Minimum Trip           180           (180A)  Test Points: @2.0X, 11.000s
         2) TF-Response                                               @5.0X, 0.747s
         3) INST                   15x          (2700A)               @10.0X, 0.230s
         4) INST-Delay             Fixed        (seconds)

-------------------------------------------------------------------------------
Device Name:      N1-M3520                               TCC Name:          TCC # 01 SWGR N1-EAST PROTECTION.tcc
Bus Name:         SWGR N1-EAST                           Bus Voltage:       4160.0V
Function Name:    Phase
Manufacturer:     BECKWITH
Description:      50/51VC, 5A
Type:             M-3520                                 Class Desc:        M-3520
AIC Rating:       N/A                                    Fault Duty:        5116.1A
Current Rating:   1200A / 5A                             Curve Multiplier: 1
Time Multiplier: 1                                       Time Adder:        0
Setting: 1) 51VC Pickup            2.5           (600A)  Test Points: @2.0X, 9.260s
         2) EINV                   4.7                                @5.0X, 1.212s
                                                                      @10.0X, 0.396s

-------------------------------------------------------------------------------
Device Name:      BT1-MIF-II                             TCC Name:          TCC # 01 SWGR N1-EAST PROTECTION.tcc
Bus Name:         SWGR N1-EAST                           Bus Voltage:       4160.0V
Function Name:    Phase
Manufacturer:     GE MULTILIN
Description:      50P/51P, ANSI
Type:             MIF II                                 Class Desc:        MIF II
AIC Rating:       N/A                                    Fault Duty:        5116.1A
Current Rating:   1200A / 5A                             Curve Multiplier: 1
Time Multiplier: 1                                       Time Adder:        0
Setting: 1) 51P TOC Pickup         0.38          (456A)  Test Points: @2.0X, 8.373s
         2) ANSI Extr Inv          4.8        1                       @5.0X, 1.188s
         3) 50P1 IOC Pickup        2.9          (3480A)               @10.0X, 0.472s
         4) 50P1 IOC Delay         0.1          (seconds)

-------------------------------------------------------------------------------
Device Name:      3/0-1-30-1                             TCC Name:          TCC # 01 SWGR N1-EAST PROTECTION.tcc
Bus Name:         COOPER iDP-210 SWGR                    Bus Voltage:       24900.0V
                                                         Curve Multiplier: 1
Time Multiplier: 1                                       Time Adder:        0
Description:      Cable Damage Curve                     Qty/Ph:            1
Size:             3/0
Material:         Copper                                 Cont. Temp:        90 deg C.
Total Ampacity:   355.0                                  Damage Temp:       250 deg C.
-------------------------------------------------------------------------------
Device Name:      350-2-75-4                             TCC Name:          TCC # 01 SWGR N1-EAST PROTECTION.tcc
Bus Name:         XFMR - N1 SEC                          Bus Voltage:       4160.0V
                                                         Curve Multiplier: 1
Time Multiplier: 1                                       Time Adder:        0
Description:      Cable Damage Curve                     Qty/Ph:            2
Size:             350
Material:         Copper                                 Cont. Temp:        90 deg C.
Total Ampacity:   1050.0                                 Damage Temp:       250 deg C.
-------------------------------------------------------------------------------
Device Name:      1/0-1-495-2                            TCC Name:          TCC # 01 SWGR N1-EAST PROTECTION.tcc
Bus Name:         25KV SWGR EXISTING                     Bus Voltage:       24900.0V
                                                         Curve Multiplier: 1
Time Multiplier: 1                                       Time Adder:        0
Description:      Cable Damage Curve                     Qty/Ph:            1
```
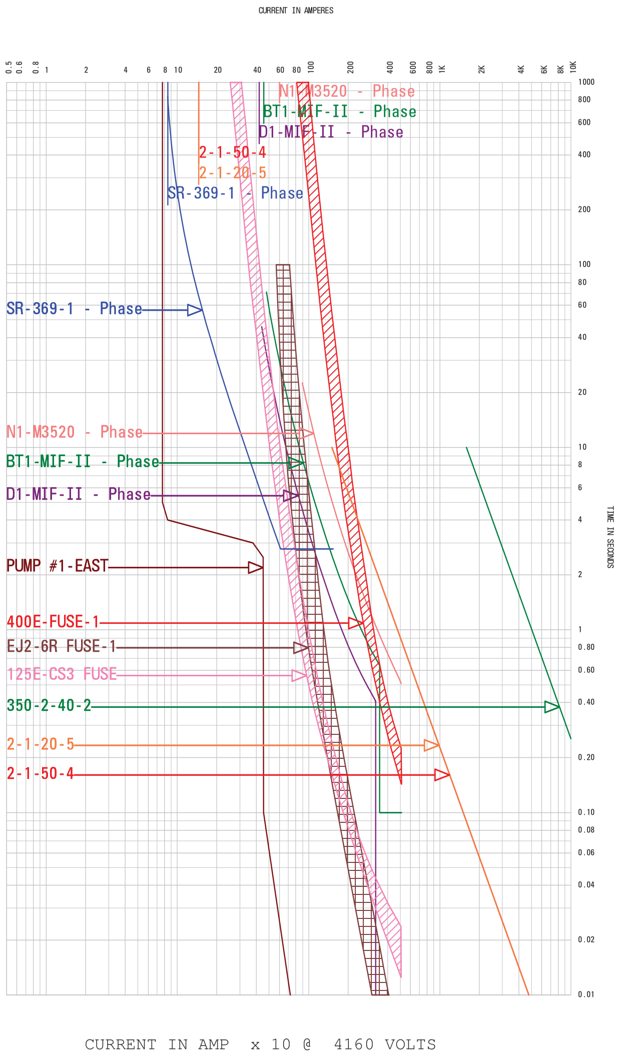
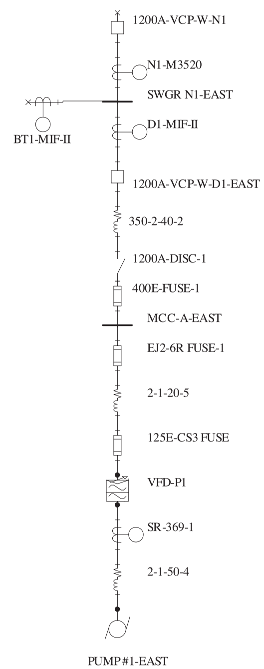

REV. 01

Attachment XI - All TCC Coordination Graphs

TCC # 01 SWGR N1-EAST PROTECTION
PROTECTIVE DEVICE COORDINATION CURVE
KAMAMA PUMP STATION
KATIA, TEXAN






```
Project Name:      KAMAMA PUMPSTATION UPGRADE(Base Project)
TCC Name:          TCC # 02 PUMP #1-EAST PROTECTION.tcc
Reference Voltage: 4160 V
Current Scale:     X 10^1
Fault Duty Option: Study Result - Bus Fault Current

------------------------------------------------------------------------------------------
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------------------------------------------------------------------------------------------

------------------------------------------------------------------------------------------
Device Name:      N1-M3520                                  TCC Name:         TCC # 02 PUMP #1-EAST PROTECTION.tcc
Bus Name:         SWGR N1-EAST                              Bus Voltage:      4160.0V
Function Name:    Phase
Manufacturer:     BECKWITH
Description:      50/51VC, 5A
Type:             M-3520                                    Class Desc:       M-3520
AIC Rating:       N/A                                       Fault Duty:       5116.1A
Current Rating:   1200A / 5A                                Curve Multiplier: 1
Time Multiplier: 1                                          Time Adder:       0
Setting: 1) 51VC Pickup         2.5         (600A)          Test Points: @2.0X, 9.260s
         2) EINV                4.7                                      @5.0X, 1.212s
                                                                         @10.0X, 0.396s

------------------------------------------------------------------------------------------
Device Name:      BT1-MIF-II                                TCC Name:         TCC # 02 PUMP #1-EAST PROTECTION.tcc
Bus Name:         SWGR N1-EAST                              Bus Voltage:      4160.0V
Function Name:    Phase
Manufacturer:     GE MULTILIN
Description:      50P/51P, ANSI
Type:             MIF II                                    Class Desc:       MIF II
AIC Rating:       N/A                                       Fault Duty:       5116.1A
Current Rating:   1200A / 5A                                Curve Multiplier: 1
Time Multiplier: 1                                          Time Adder:       0
Setting: 1) 51P TOC Pickup      0.38        (456A)          Test Points: @2.0X, 8.373s
         2) ANSI Extr Inv       4.8      1                               @5.0X, 1.188s
         3) 50P1 IOC Pickup     2.9         (3480A)                      @10.0X, 0.472s
         4) 50P1 IOC Delay      0.1         (seconds)

------------------------------------------------------------------------------------------
Device Name:      D1-MIF-II                                 TCC Name:         TCC # 02 PUMP #1-EAST PROTECTION.tcc
Bus Name:         SWGR N1-EAST                              Bus Voltage:      4160.0V
Function Name:    Phase
Manufacturer:     GE MULTILIN
Description:      50P/51P, ANSI
Type:             MIF II                                    Class Desc:       MIF II
AIC Rating:       N/A                                       Fault Duty:       5116.1A
Current Rating:   1200A / 5A                                Curve Multiplier: 1
Time Multiplier: 1                                          Time Adder:       0
Setting: 1) 51P TOC Pickup      0.35        (420A)          Test Points: @2.0X, 5.407s
         2) ANSI Extr Inv       3.1      1                               @5.0X, 0.767s
         3) 50P1 IOC Pickup     2.7         (3240A)                      @10.0X, 0.305s

------------------------------------------------------------------------------------------
Device Name:      400E-FUSE-1                               TCC Name:         TCC # 02 PUMP #1-EAST PROTECTION.tcc
Bus Name:         MCC-A-EAST                                Bus Voltage:      4160.0V
Function Name:    Phase
Manufacturer:     GOULD SHAWMUT
Description:      10E-450E
Type:             CS-3, 5.5kV E-Rated
AIC Rating:       63kA                                      Fault Duty:       5107.8A
Cartridge:        CS-3, 400E 5500V 400A                     Curve Multiplier: 1
Time Multiplier: 1                                          Time Adder:       0
Size:             400A

------------------------------------------------------------------------------------------
Device Name:      EJ2-6R FUSE-1                             TCC Name:         TCC # 02 PUMP #1-EAST PROTECTION.tcc
Bus Name:         MCC-A-EAST                                Bus Voltage:      4160.0V
Function Name:    Phase
Manufacturer:     GE
Description:      2R-36R
Type:             9F60 EJ-2, 2.54 & 5.08kV R-Rated
AIC Rating:       50kA                                      Fault Duty:       5107.8A
Cartridge:        EJ-2, 6R 5080V 170A                       Curve Multiplier: 1
Time Multiplier: 1                                          Time Adder:       0
Size:             170A

------------------------------------------------------------------------------------------
Device Name:      125E-CS3 FUSE                             TCC Name:         TCC # 02 PUMP #1-EAST PROTECTION.tcc
Bus Name:         VFD P1 IN                                 Bus Voltage:      4160.0V
Function Name:    Phase
Manufacturer:     GOULD SHAWMUT
Description:      10E-450E
Type:             CS-3, 5.5kV E-Rated
AIC Rating:       63kA                                      Fault Duty:       5087.8A
Cartridge:        CS-3, 125E 5500V 125A                     Curve Multiplier: 1
Time Multiplier: 1                                          Time Adder:       0
Size:             125A

------------------------------------------------------------------------------------------
Device Name:      SR-369-1                                  TCC Name:         TCC # 02 PUMP #1-EAST PROTECTION.tcc
Bus Name:         VFD-P1 OUT                                Bus Voltage:      4160.0V
Function Name:    Phase
Manufacturer:     GE MULTILIN
Description:      50/51, 5A CT Sec
Type:             369 Motor Relay                           Class Desc:       369
Fault Duty:       5237.2A                                   Curve Multiplier: 1
Time Multiplier: 1                                          Time Adder:       0
Current Rating:   100A / 5A                                 FLA:              76.90A
Setting: 1) O/L PU              1.1         (84.6A)         Test Points: @2.0X, 58.320s
         2) Standard O/L Curve  2                                        @5.0X, 7.290s

------------------------------------------------------------------------------------------
Device Name:      350-2-40-2                                TCC Name:         TCC # 02 PUMP #1-EAST PROTECTION.tcc
Bus Name:         SWGR N1-EAST                              Bus Voltage:      4160.0V
                                                            Curve Multiplier: 1
Time Multiplier: 1                                          Time Adder:       0
```
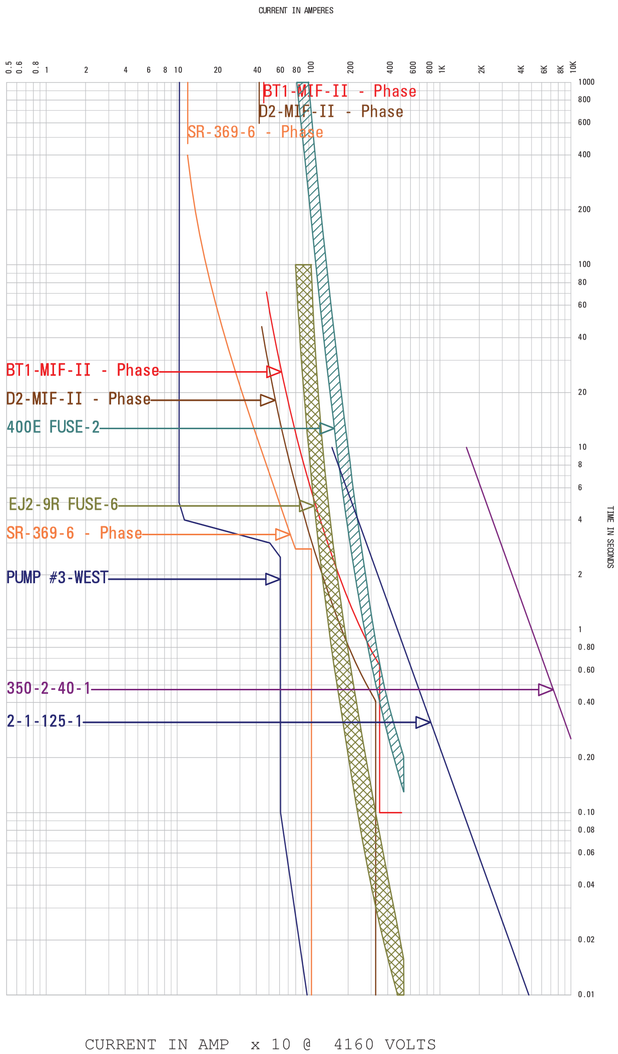
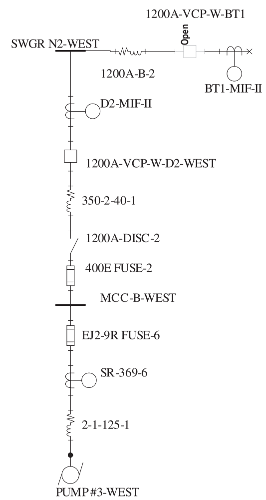

REV. 01

TCC # 02 PUMP #1-EAST PROTECTION
PROTECTIVE DEVICE COORDINATION CURVE
KAMAMA PUMP STATION
KATIA, TEXANA






```
Project Name:      KAMAMA PUMPSTATION UPGRADE(Base Project)
TCC Name:          TCC # 03 PUMP #3-WEST PROTECTION.tcc
Reference Voltage: 4160 V
Current Scale:     X 10^1
Fault Duty Option: Study Result - Bus Fault Current

------------------------------------------------------------------------------------------
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------------------------------------------------------------------------------------------
Device Name:     BT1-MIF-II                                TCC Name:         TCC # 03 PUMP #3-WEST PROTECTION.tcc
Bus Name:        SWGR N1-EAST                              Bus Voltage:      4160.0V
Function Name:   Phase
Manufacturer:    GE MULTILIN
Description:     50P/51P, ANSI
Type:            MIF II                                    Class Desc:       MIF II
AIC Rating:      N/A                                       Fault Duty:       5116.1A
Current Rating:  1200A / 5A                                Curve Multiplier: 1
Time Multiplier: 1                                         Time Adder:       0
Setting: 1) 51P TOC Pickup        0.38          (456A)     Test Points: @2.0X, 8.373s
         2) ANSI Extr Inv         4.8        1                          @5.0X, 1.188s
         3) 50P1 IOC Pickup       2.9           (3480A)                 @10.0X, 0.472s
         4) 50P1 IOC Delay        0.1           (seconds)

------------------------------------------------------------------------------------------
Device Name:     D2-MIF-II                                 TCC Name:         TCC # 03 PUMP #3-WEST PROTECTION.tcc
Bus Name:        SWGR N2-WEST                              Bus Voltage:      4160.0V
Function Name:   Phase
Manufacturer:    GE MULTILIN
Description:     50P/51P, ANSI
Type:            MIF II                                    Class Desc:       MIF II
AIC Rating:      N/A                                       Fault Duty:       5341.0A
Current Rating:  1200A / 5A                                Curve Multiplier: 1
Time Multiplier: 1                                         Time Adder:       0
Setting: 1) 51P TOC Pickup        0.35          (420A)     Test Points: @2.0X, 5.407s
         2) ANSI Extr Inv         3.1        1                          @5.0X, 0.767s
         3) 50P1 IOC Pickup       2.7           (3240A)                 @10.0X, 0.305s

------------------------------------------------------------------------------------------
Device Name:     400E FUSE-2                               TCC Name:         TCC # 03 PUMP #3-WEST PROTECTION.tcc
Bus Name:        MCC-B-WEST                                Bus Voltage:      4160.0V
Function Name:   Phase
Manufacturer:    GOULD SHAWMUT
Description:     10E-450E
Type:            CS-3, 5.5kV E-Rated
AIC Rating:      63kA                                      Fault Duty:       5332.8A
Cartridge:       CS-3, 400E 5500V 400A                     Curve Multiplier: 1
Time Multiplier: 1                                         Time Adder:       0
Size:            400A

------------------------------------------------------------------------------------------
Device Name:     EJ2-9R FUSE-6                             TCC Name:         TCC # 03 PUMP #3-WEST PROTECTION.tcc
Bus Name:        MCC-B-WEST                                Bus Voltage:      4160.0V
Function Name:   Phase
Manufacturer:    GE
Description:     2R-36R
Type:            9F60 EJ-2, 2.54 & 5.08kV R-Rated
AIC Rating:      50kA                                      Fault Duty:       5332.8A
Cartridge:       EJ-2, 9R 5080V 200A                       Curve Multiplier: 1
Time Multiplier: 1                                         Time Adder:       0
Size:            200A

------------------------------------------------------------------------------------------
Device Name:     SR-369-6                                  TCC Name:         TCC # 03 PUMP #3-WEST PROTECTION.tcc
Bus Name:        MCC-B-WEST                                Bus Voltage:      4160.0V
Function Name:   Phase
Manufacturer:    GE MULTILIN
Description:     50/51, 5A CT Sec
Type:            369 Motor Relay                           Class Desc:       369
Fault Duty:      5332.8A                                   Curve Multiplier: 1
Time Multiplier: 1                                         Time Adder:       0
Current Rating:  150A / 5A                                 FLA:              100.00A
Setting: 1) O/L PU                1.2           (120A)     Test Points: @2.0X, 58.320s
         2) Standard O/L Curve    2                                     @5.0X, 7.290s
         3) S/C Trip              7             (1050A)                 @10.0X, 3.087s

------------------------------------------------------------------------------------------
Device Name:     1200A-VCP-W-D2-WEST                       TCC Name:         TCC # 03 PUMP #3-WEST PROTECTION.tcc
Bus Name:        SWGR N2-WEST                              Bus Voltage:      4160.0V
Function Name:   Phase
Manufacturer:    CUTLER-HAMMER
Description:     600-3000A
Type:            VCP-W
AIC Rating:      29kA                                      Fault Duty:       5341.0A
Frame:           50 VCP-W-250 4760V 1200A                  Curve Multiplier: 1
Time Multiplier: 1                                         Time Adder:       0
Sensor:
Plug:

------------------------------------------------------------------------------------------
Device Name:     350-2-40-1                                TCC Name:         TCC # 03 PUMP #3-WEST PROTECTION.tcc
Bus Name:        SWGR N2-WEST                              Bus Voltage:      4160.0V
                                                           Curve Multiplier: 1
Time Multiplier: 1                                         Time Adder:       0
Description:     Cable Damage Curve                        Qty/Ph:           2
Size:            350
Material:        Copper                                    Cont. Temp:       90 deg C.
Total Ampacity:  790.0                                     Damage Temp:      250 deg C.
------------------------------------------------------------------------------------------
Device Name:     2-1-125-1                                 TCC Name:         TCC # 03 PUMP #3-WEST PROTECTION.tcc
Bus Name:        MCC-B-WEST                                Bus Voltage:      4160.0V
                                                           Curve Multiplier: 1
Time Multiplier: 1                                         Time Adder:       0
Description:     Cable Damage Curve                        Qty/Ph:           1
Size:            2
Material:        Copper                                    Cont. Temp:       90 deg C.
```
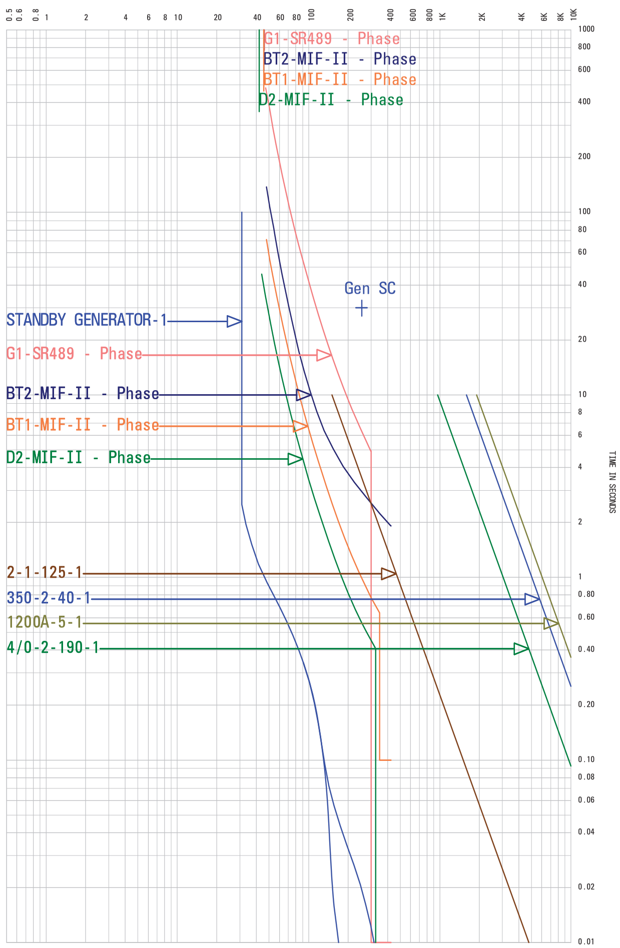
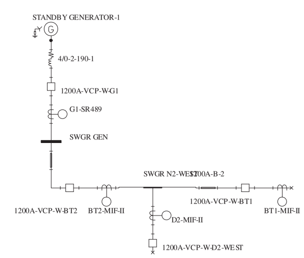

REV. 01

TCC # 03 PUMP #3-WEST PROTECTION
PROTECTIVE DEVICE COORDINATION CURVE
KAMAMA PUMP STATION
KATIA, TEXANA






```
Project Name:      KAMAMA PUMPSTATION UPGRADE(EMERGENCY OPERATIN - REV 01)
TCC Name:          TCC # 04 GENERATOR MCC-B-WEST PROTECTION.tcc
Reference Voltage: 4160 V
Current Scale:     X 10^1
Fault Duty Option: Study Result - Bus Fault Current

-----------------------------------------------------------------------------------------
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-----------------------------------------------------------------------------------------
Device Name:     G1-SR489                                 TCC Name:         TCC # 04 GENERATOR MCC-B-WEST PROTECTION.tcc
Bus Name:        SWGR GEN                                 Bus Voltage:      4160.0V
Function Name:   Phase
Manufacturer:    GE MULTILIN
Description:     50/51, 5A CT
Type:            489                                      Class Desc:       489
Fault Duty:      4256.6A                                  Curve Multiplier: 1
Time Multiplier: 1                                        Time Adder:       0
Current Rating:  500A / 5A                                FLA:              390.00A
Setting: 1) Phase OC Pickup        0.92         (460A)    Test Points: @2.0X, 52.330s
         2) ANSI Ext Inverse       30          1                     @5.0X, 7.422s
         3) High-Set OC Pickup     6            (3000A)              @10.0X, 2.947s
         4) High-Set OC Delay      0.01        (seconds)

-----------------------------------------------------------------------------------------
Device Name:     BT2-MIF-II                               TCC Name:         TCC # 04 GENERATOR MCC-B-WEST PROTECTION.tcc
Bus Name:        SWGR N2-WEST                             Bus Voltage:      4160.0V
Function Name:   Phase
Manufacturer:    GE MULTILIN
Description:     50P/51P, ANSI
Type:            MIF II                                   Class Desc:       MIF II
AIC Rating:      N/A                                      Fault Duty:       4256.1A
Current Rating:  1200A / 5A                               Curve Multiplier: 1
Time Multiplier: 1                                        Time Adder:       0
Setting: 1) 51P TOC Pickup         0.38         (456A)    Test Points: @2.0X, 14.125s
         2) ANSI Inverse           8           1                     @5.0X, 3.254s
         3) 50P1 IOC Pickup        4           (4800A)               @10.0X, 1.808s
         4) 50P1 IOC Delay         0.4          (seconds)

-----------------------------------------------------------------------------------------
Device Name:     BT1-MIF-II                               TCC Name:         TCC # 04 GENERATOR MCC-B-WEST PROTECTION.tcc
Bus Name:        SWGR N1-EAST                             Bus Voltage:      4160.0V
Function Name:   Phase
Manufacturer:    GE MULTILIN
Description:     50P/51P, ANSI
Type:            MIF II                                   Class Desc:       MIF II
AIC Rating:      N/A                                      Fault Duty:       4254.3A
Current Rating:  1200A / 5A                               Curve Multiplier: 1
Time Multiplier: 1                                        Time Adder:       0
Setting: 1) 51P TOC Pickup         0.38         (456A)    Test Points: @2.0X, 8.373s
         2) ANSI Extr Inv          4.8         1                     @5.0X, 1.188s
         3) 50P1 IOC Pickup        2.9          (3480A)              @10.0X, 0.472s
         4) 50P1 IOC Delay         0.1          (seconds)

-----------------------------------------------------------------------------------------
Device Name:     D2-MIF-II                                TCC Name:         TCC # 04 GENERATOR MCC-B-WEST PROTECTION.tcc
Bus Name:        SWGR N2-WEST                             Bus Voltage:      4160.0V
Function Name:   Phase
Manufacturer:    GE MULTILIN
Description:     50P/51P, ANSI
Type:            MIF II                                   Class Desc:       MIF II
AIC Rating:      N/A                                      Fault Duty:       4256.1A
Current Rating:  1200A / 5A                               Curve Multiplier: 1
Time Multiplier: 1                                        Time Adder:       0
Setting: 1) 51P TOC Pickup         0.35         (420A)    Test Points: @2.0X, 5.407s
         2) ANSI Extr Inv          3.1         1                     @5.0X, 0.767s
         3) 50P1 IOC Pickup        2.7          (3240A)              @10.0X, 0.305s

-----------------------------------------------------------------------------------------
Device Name:     2-1-125-1                                TCC Name:         TCC # 04 GENERATOR MCC-B-WEST PROTECTION.tcc
Bus Name:        MCC-B-WEST                               Bus Voltage:      4160.0V
                                                          Curve Multiplier: 1
Time Multiplier: 1                                        Time Adder:       0
Description:     Cable Damage Curve                       Qty/Ph:           1
Size:            2
Material:        Copper                                   Cont. Temp:       90 deg C.
Total Ampacity:  145.0                                    Damage Temp:      250 deg C.
-----------------------------------------------------------------------------------------
Device Name:     350-2-40-1                               TCC Name:         TCC # 04 GENERATOR MCC-B-WEST PROTECTION.tcc
Bus Name:        SWGR N2-WEST                             Bus Voltage:      4160.0V
                                                          Curve Multiplier: 1
Time Multiplier: 1                                        Time Adder:       0
Description:     Cable Damage Curve                       Qty/Ph:           2
Size:            350
Material:        Copper                                   Cont. Temp:       90 deg C.
Total Ampacity:  790.0                                    Damage Temp:      250 deg C.
-----------------------------------------------------------------------------------------
Device Name:     1200A-5-1                                TCC Name:         TCC # 04 GENERATOR MCC-B-WEST PROTECTION.tcc
Bus Name:        SWGR GEN                                 Bus Voltage:      4160.0V
                                                          Curve Multiplier: 1
Time Multiplier: 1                                        Time Adder:       0
Description:     Cable Damage Curve                       Qty/Ph:           1
Size:            1200
Material:        Copper                                   Cont. Temp:       65 deg C.
Total Ampacity:  1200.0                                   Damage Temp:      130 deg C.
-----------------------------------------------------------------------------------------
Device Name:     4/0-2-190-1                              TCC Name:         TCC # 04 GENERATOR MCC-B-WEST PROTECTION.tcc
Bus Name:        STANDBY GEN                              Bus Voltage:      4160.0V
                                                          Curve Multiplier: 1
Time Multiplier: 1                                        Time Adder:       0
Description:     Cable Damage Curve                       Qty/Ph:           2
Size:            4/0
Material:        Copper                                   Cont. Temp:       90 deg C.
Total Ampacity:  510.0                                    Damage Temp:      250 deg C.
-----------------------------------------------------------------------------------------
Device Name:     1200A-DISC-2                             TCC Name:         TCC # 04 GENERATOR MCC-B-WEST PROTECTION.tcc
```
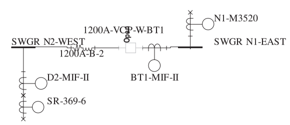

REV. 01

TCC # 04 GENERATOR MCC-B-WEST PROTECTION
PROTECTIVE DEVICE COORDINATION CURVE
KAMAMA PUMP STATION
KATIA, TEXANA

CURRENT IN AMP x 1 @ 4160 VOLTS



Project Name: KAMAMA PUMPSTATION UPGRADE(Base Project)
TCC Name: TCC # 05 SWGR N1-EAST GROUND FAULT PROTECTION.tcc
Reference Voltage: 4160 V
Current Scale: X 10^0
Fault Duty Option: Study Result - Bus Fault Current

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Device Name: N1-M3520 — TCC Name: TCC # 05 SWGR N1-EAST GROUND FAULT PROTECTION.tcc
Bus Name: SWGR N1-EAST — Bus Voltage: 4160.0V
Function Name: GROUND
Manufacturer: BECKWITH
Description: 50G/51G, 5A
Type: M-3520 — Class Desc: M-3520
AIC Rating: N/A — Fault Duty: 389.2A
Current Rating: 200A / 5A — Curve Multiplier: 1
Time Multiplier: 1 — Time Adder: 0
Setting: 1) 51G Pickup 3.8 (152A) — Test Points: @2.0X, 1.592s
2) EINV 0.8 — @5.0X, 0.212s
3) 50G Pickup 10 (400A) — @10.0X, 0.067s

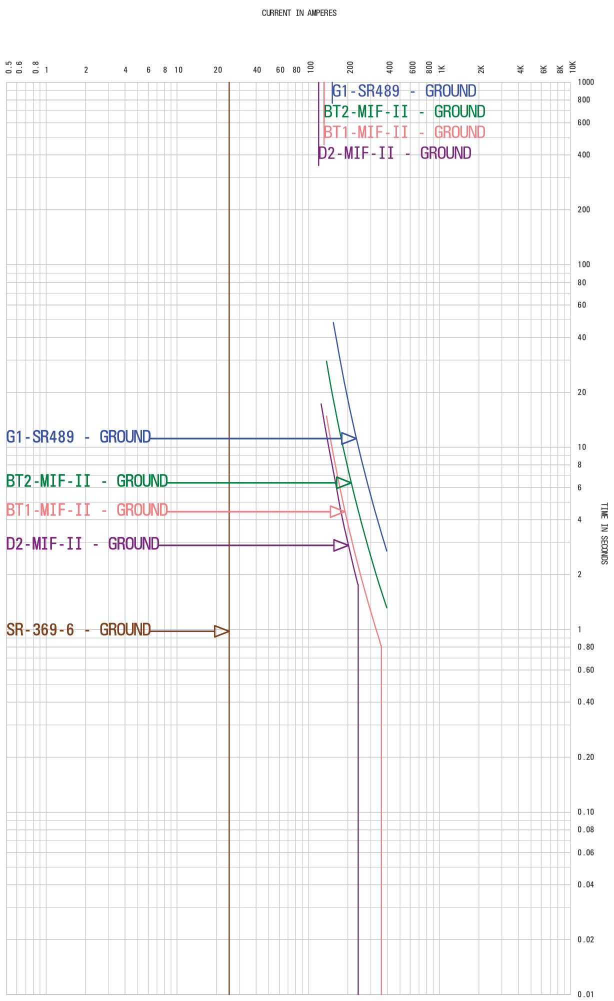
Device Name: BT1-MIF-II — TCC Name: TCC # 05 SWGR N1-EAST GROUND FAULT PROTECTION.tcc
Bus Name: SWGR N1-EAST — Bus Voltage: 4160.0V
Function Name: GROUND
Manufacturer: GE MULTILIN
Description: 50G/51G, ANSI
Type: MIF II — Class Desc: MIF II
AIC Rating: N/A — Fault Duty: 389.2A
Current Rating: 1200A / 5A — Curve Multiplier: 1
Time Multiplier: 1 — Time Adder: 0
Setting: 1) 51G TOC Pickup 0.11 (132A) — Test Points: @2.0X, 1.744s
2) ANSI Extr Inv 1 1 — @5.0X, 0.247s
3) 50G1 IOC Pickup 0.3 (360A) — @10.0X, 0.098s

Device Name: D2-MIF-II — TCC Name: TCC # 05 SWGR N1-EAST GROUND FAULT PROTECTION.tcc
Bus Name: SWGR N2-WEST — Bus Voltage: 4160.0V
Function Name: GROUND
Manufacturer: GE MULTILIN
Description: 50G/51G, ANSI
Type: MIF II — Class Desc: MIF II
AIC Rating: N/A — Fault Duty: 389.5A
Current Rating: 1200A / 5A — Curve Multiplier: 1
Time Multiplier: 1 — Time Adder: 0
Setting: 1) 51G TOC Pickup 0.1 (120A) — Test Points: @2.0X, 1.766s
2) ANSI Inverse 1 1 — @5.0X, 0.407s
3) 50G1 IOC Pickup 0.2 (240A) — @10.0X, 0.226s

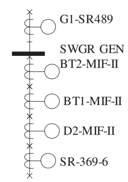
Device Name: SR-369-6 — TCC Name: TCC # 05 SWGR N1-EAST GROUND FAULT PROTECTION.tcc
Bus Name: MCC-B-WEST — Bus Voltage: 4160.0V
Function Name: GROUND
Manufacturer: GE MULTILIN
Description: 50G/51G, 50:0.025 CT
Type: 369 Motor Relay — Class Desc: 369
Fault Duty: 389.5A — Curve Multiplier: 1
Time Multiplier: 1 — Time Adder: 0
Current Rating: 50A / 0.02A — FLA: 100.00A
Setting: 1) GFPU (0.25-25A) 25 (25A) — Test Points: @2.0X, 0.010s

REV. 01

TCC # 05 SWGR N1-EAST GROUND FAULT PROTECTION
PROTECTIVE DEVICE COORDINATION CURVE
KAMAMA PUMP STATION
KATIA, TEXANA



CURRENT IN AMP x 1 @ 4160 VOLTS




```
Project Name:      KAMAMA PUMPSTATION UPGRADE(EMERGENCY OPERATIN - REV 01)
TCC Name:          TCC # 06 GENERATOR -1 GROUND FAULT PROTECTION.tcc
Reference Voltage: 4160 V
Current Scale:     X 10^0
Fault Duty Option: Study Result - Bus Fault Current

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---------------------------------------------------------------------------------------
Device Name:     G1-SR489                              TCC Name:         TCC # 06 GENERATOR -1 GROUND FAULT PROTECTION.tcc
Bus Name:        SWGR GEN                              Bus Voltage:      4160.0V
Function Name:   GROUND
Manufacturer:    GE MULTILIN
Description:     50/51GN, 5A CT
Type:            489                                   Class Desc:       489
Fault Duty:      397.3A                                Curve Multiplier: 1
Time Multiplier: 1                                     Time Adder:       0
Current Rating:  200A / 5A                             FLA:              390.00A
Setting: 1) GF OC Pickup          0.76          (152A)  Test Points: @2.0X, 5.233s
         2) ANSI Ext Inverse      3           1                      @5.0X, 0.742s

---------------------------------------------------------------------------------------
Device Name:     BT2-MIF-II                            TCC Name:         TCC # 06 GENERATOR -1 GROUND FAULT PROTECTION.tcc
Bus Name:        SWGR N2-WEST                          Bus Voltage:      4160.0V
Function Name:   GROUND
Manufacturer:    GE MULTILIN
Description:     50G/51G, ANSI
Type:            MIF II                                Class Desc:       MIF II
AIC Rating:      N/A                                   Fault Duty:       397.3A
Current Rating:  1200A / 5A                            Curve Multiplier: 1
Time Multiplier: 1                                     Time Adder:       0
Setting: 1) 51G TOC Pickup        0.11          (132A)  Test Points: @2.0X, 3.489s
         2) ANSI Extr Inv         2           1                      @5.0X, 0.495s
         3) 50G1 IOC Pickup       0.4           (480A)               @10.0X, 0.196s

---------------------------------------------------------------------------------------
Device Name:     D2-MIF-II                             TCC Name:         TCC # 06 GENERATOR -1 GROUND FAULT PROTECTION.tcc
Bus Name:        SWGR N2-WEST                          Bus Voltage:      4160.0V
Function Name:   GROUND
Manufacturer:    GE MULTILIN
Description:     50G/51G, ANSI
Type:            MIF II                                Class Desc:       MIF II
AIC Rating:      N/A                                   Fault Duty:       397.3A
Current Rating:  1200A / 5A                            Curve Multiplier: 1
Time Multiplier: 1                                     Time Adder:       0
Setting: 1) 51G TOC Pickup        0.1          (120A)   Test Points: @2.0X, 1.766s
         2) ANSI Inverse          1           1                      @5.0X, 0.407s
         3) 50G1 IOC Pickup       0.2           (240A)               @10.0X, 0.226s

---------------------------------------------------------------------------------------
Device Name:     SR-369-6                              TCC Name:         TCC # 06 GENERATOR -1 GROUND FAULT PROTECTION.tcc
Bus Name:        MCC-B-WEST                            Bus Voltage:      4160.0V
Function Name:   GROUND
Manufacturer:    GE MULTILIN
Description:     50G/51G, 50:0.025 CT
Type:            369 Motor Relay                       Class Desc:       369
Fault Duty:      397.2A                                Curve Multiplier: 1
Time Multiplier: 1                                     Time Adder:       0
Current Rating:  50A / 0.02A                           FLA:              100.00A
Setting: 1) GFPU (0.25-25A)       25           (25A)    Test Points: @2.0X, 0.010s

---------------------------------------------------------------------------------------
Device Name:     BT1-MIF-II                            TCC Name:         TCC # 06 GENERATOR -1 GROUND FAULT PROTECTION.tcc
Bus Name:        SWGR N1-EAST                          Bus Voltage:      4160.0V
Function Name:   GROUND
Manufacturer:    GE MULTILIN
Description:     50G/51G, ANSI
Type:            MIF II                                Class Desc:       MIF II
AIC Rating:      N/A                                   Fault Duty:       397.3A
Current Rating:  1200A / 5A                            Curve Multiplier: 1
Time Multiplier: 1                                     Time Adder:       0
Setting: 1) 51G TOC Pickup        0.11          (132A)  Test Points: @2.0X, 1.744s
         2) ANSI Extr Inv         1           1                      @5.0X, 0.247s
         3) 50G1 IOC Pickup       0.3           (360A)               @10.0X, 0.098s
```

REV. 01

TCC # 06 GENERATOR -1 GROUND FAULT PROTECTION
PROTECTIVE DEVICE COORDINATION CURVE
KAMAMA PUMP STATION
KATIA, TEXANA

Attachment XII - DEVICE SETTINGS SHEET

FOR KAMAMA PUMP STATION IN KATIA, TEXANA

REVISION: 01 DATE: 03/31/2015

SERVICE			RELAY DESCRIPTION						RANGE		SETTINGS						
SERVING	LOCATION	ONELINE TAG	RELAY TAG	PHASE	MFG.	MODEL NO.	TIME CHAR	INST BOOK #	TIME	INST	CT. OR PT. RATIO	TAP	TIME DIAL	INST	INST DELAY	TCC NUMBER	REMARKS
25kV COOPER IDP-210 SWGR																	
25KV SWGR EXISTING	25KV SWGR EXISTING	iDP-210	50/51	ABC	COOPER	iDP-210	IEEE EI	Apparatus 165-210	0.025-90A	0.1-10	200/1	1.025	2	---	---	1	
25kV SWGR EXISTING																	
XFMR-N1-EAST FEEDER	25KV SWGR EXISTING	COOPER SWGR-N1	50/51	ABC	COOPER	VFI	TF-RESPONSE	Apparatus 285-10	20-1290	0.5-240	200/1	180	TR	15X	FIXED	1	
XFMR-N2-WEST FEEDER	25KV SWGR EXISTING	COOPER SWGR-N2	50/51	ABC	COOPER	VFI	TF-RESPONSE	Apparatus 285-10	20-1290	0.5-240	200/1	180	TR	15X	FIXED	1	
3750kVA XFMR N1-EAST & N2-WEST PRIMARY																	
XFMR-N1-EAST	XFMR-N1-EAST PRIMARY	COOPER XFMR-N1	50/51	ABC	COOPER	VFI	TF-RESPONSE	Apparatus 285-10	20-1290	0.5-240	200/1	180	TR	15X	FIXED	1	
XFMR-N2-WEST	XFMR-N2-WEST PRIMARY	COOPER XFMR-N2	50/51	ABC	COOPER	VFI	TF-RESPONSE	Apparatus 285-10	20-1290	0.5-240	200/1	180	TR	15X	FIXED	1	
4160V SWGR N1-EAST																	
SWGR N1-EAST MAIN	SWGR N1-EAST	N1-M3520	50/51	ABC	BECKWITH	M3520	EXT INV	800-3520-IB-09MC4	0.5 - 12	0.1 - 240	1200/5	2.5	4.7	---	---	1, 2	
			50G/51G	N	BECKWITH	M3520	EXT INV	800-3520-IB-09MC4	0.5 - 12	0.1 - 240	200/5	3.8	0.8	10	---	5	
SWGR N1 - N2 TIE BREAKER	SWGR N1-WEST	BT1-MIF-II	50/51	ABC	GE MULTILIN	MIF	EXT INV	GEK-106273L	0.1 - 2.4	1 - 30	1200/5	0.38	4.8	2.9	0.1	1, 2, 3, 4	
			50G/51G	N	GE MULTILIN	MIF	EXT INV	GEK-106273L	0.1 - 2.4	1 - 30	1200/5	0.11	1	0.3	---	5, 6	
MCC-A-EAST FEEDER	SWGR N1-EAST	D1-MIF-II	50/51	ABC	GE MULTILIN	MIF	EXT INV	GEK-106273L	0.1 - 2.4	1 - 30	1200/5	0.35	3.1	2.7	---	2	
			50G/51G	N	GE MULTILIN	MIF	EXT INV	GEK-106273L	0.1 - 2.4	1 - 30	1200/5	0.1	1	0.2	---	5,6	

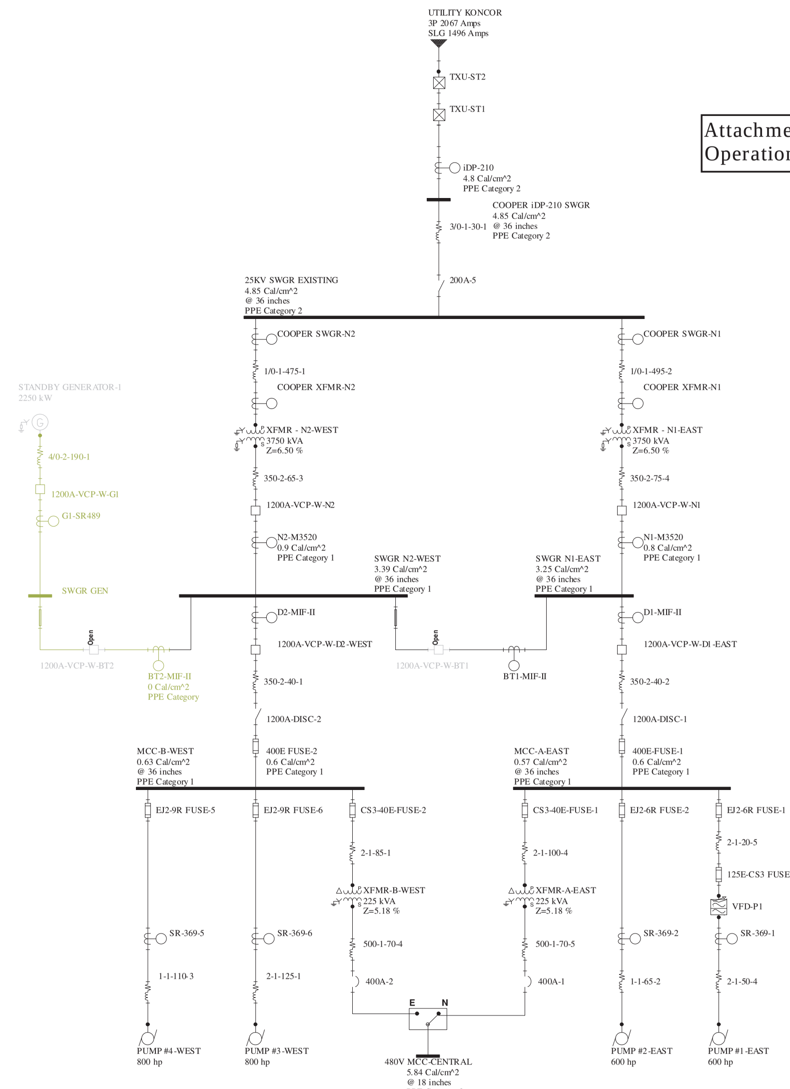
Attachment XII - DEVICE SETTINGS SHEET

FOR KAMAMA PUMP STATION IN KATIA, TEXANA

REVISION: 01　　　　DATE: 03/31/2015

SERVICE			RELAY DESCRIPTION								SETTINGS						
SERVING	LOCATION	ONELINE TAG	RELAY TAG	PHASE	MFG.	MODEL NO.	TIME CHAR	INST BOOK #	RANGE TIME	RANGE INST	CT. OR PT. RATIO	TAP	TIME DIAL	INST	INST DELAY	TCC NUMBER	REMARKS
4160V SWGR N2-WEST																	
SWGR N2-WEST MAIN	SWGR N2-WEST	N2-M3520	50/51	ABC	BECKWITH	M3520	EXT INV	800-3520-IB-09MC4	0.5 - 12	0.5-240	1200/5	2.5	4.7	---	---	1, 2	
			50G/51G	N	BECKWITH	M3520	EXT INV	800-3520-IB-09MC4	0.5 - 12	0.1 - 240	200/5	3.8	0.8	10	---	5	
SWGR N2 - GEN TIE BREAKER	SWGR N2-WEST	BT2-MIF-II	50/51	ABC	GE MULTILIN	MIF	EXT INV	GEK-106273L	0.1 - 2.4	1 - 30	1200/5	0.38	8	4	0.4	4	
			50G/51G	N	GE MULTILIN	MIF	EXT INV	GEK-106273L	0.1 - 2.4	1 - 30	1200/5	0.11	2	0.4	---	6	
MCC-B-WEST FEEDER	SWGR N2-WEST	D2-MIF-II	50/51	ABC	GE MULTILIN	MIF	EXT INV	GEK-106273L	0.1 - 2.4	1 - 30	1200/5	0.35	3.1	2.7	---	3,4	
			50G/51G	N	GE MULTILIN	MIF	EXT INV	GEK-106273L	0.1 - 2.4	1 - 30	1200/5	0.1	1	0.2	---	5, 6	
4160V SWGR GEN																	
STAND BY GEN-1 BREAKER	SWGR GEN	G1-SR489	50/51	ABC	GE MULTILIN	SR-489	EXT-INV	GEK-106494C	0.15 - 20	0.15-20	500/5	0.92	30	6	0.01	4	
			50/51GN	ABC	GE MULTILIN	SR-489	EXT-INV	GEK-106494C	0.15 - 20	0.15-20	200/5	0.76	3	1	---	6	
4160V MCC-A-EAST																	
PUMP # 1-EAST FEEDER	MCC-A-EAST	SR-369-1	50/51	ABC	GE MULTILIN	SR-369	ADJUSTABLE	GEK-106288G	1.01 - 1.25	1-15	100/5	1.1	2	----	---	2	
			50G/51G	N	GE MULTILIN	SR-369	ADJUSTABLE	GEK-106288G	1.01 - 1.25	1-15	50/0.025	25	---	---	---	5, 6	
PUMP # 2-EAST FEEDER	MCC-A-EAST	SR-369-2	50/51	ABC	GE MULTILIN	SR-369	ADJUSTABLE	GEK-106288G	1.01 - 1.25	1-15	100/5	1.1	2	---	---	2	
			50G/51G	N	GE MULTILIN	SR-369	ADJUSTABLE	GEK-106288G	1.01 - 1.25	1-15	50/0.025	25	---	---	---	5,6	
4160V MCC-B																	
PUMP # 4-WEST FEEDER	MCC-B-WEST	SR-369-5	50/51	ABC	GE MULTILIN	SR-369	ADJUSTABLE	GEK-106288G	1.01 - 1.25	1-15	150/5	1.2	2	S/C TRIP - 7	---	3	
			50G/51G	N	GE MULTILIN	SR-369	ADJUSTABLE	GEK-106288G	1.01 - 1.25	1-15	50/0.025	25	---	---	---	5, 6	
PUMP # 3-WEST FEEDER	MCC-B-WEST	SR-369-6	50/51	ABC	GE MULTILIN	SR-369	ADJUSTABLE	GEK-106288G	1.01 - 1.25	1-15	150/5	1.2	2	S/C TRIP - 7	---	3	
			50G/51G	N	GE MULTILIN	SR-369	ADJUSTABLE	GEK-106288G	1.01 - 1.25	1-15	50/0.025	25	---	---	---	5, 6	

Attachment XIII - Arc Flash Study One-Line Diagrams – Normal Operation

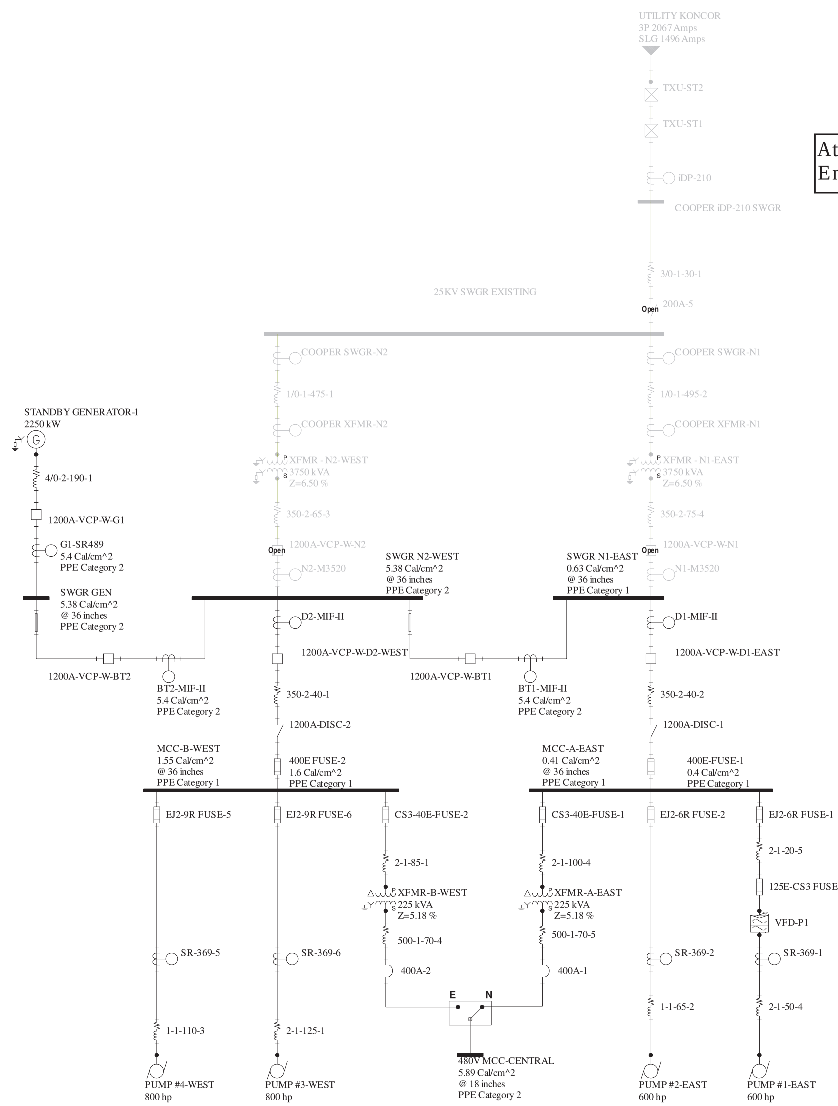


REV. 01

ARC FLASH STUDY ONELINE DIAGRAM - MAIN
KAMAMA PUMP STATION
KATIA, TEXANA

NORMAL OPERATION

Attachment XIV - Arc Flash Study One-Line Diagrams – Emergency Operation



REV. 01

ARC FLASH STUDY ONELINE DIAGRAM - MAIN
KAMAMA PUMP STATION
KATIA, TEXANA

EMERGENCY OPERATION

	Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Ground	Equip Type	Gap (mm)	Arc Flash Boundary (in)	Working Distance (in)	Incident Energy (cal/cm2)	PPE Level / Notes (*N)	Label #	Cable Length From Trip Device (ft)	Incident Energy at Low Marginal	Incident Energy at High Marginal	User Notes
1	25KV SWGR EXISTING	COOPER SWGR-N1	24.90	2.30	2.30	0.07	0.07	0.083	0.000	Yes	SWG	152	56	36	2.9	(*N11)					
2	25KV SWGR EXISTING	N2-M3520 (COOPER SWGR-N2)	24.90	2.30	2.30	0.18	0.18	0.083	0.000	Yes	SWG	152	56	36	2.9	(*N5) (*N11)		65.00			
3	25KV SWGR EXISTING	TXU-ST1	24.90	2.30	2.30	2.07	2.07	0.061	0.083	Yes	SWG	152	72	36	4.8	(*N11)	# 0001	31.00			
4																					
5	480V MCC-CENTRAL	CS3-40E-FUSE-1	0.48	4.42	2.77	4.42	2.77	0.711	0.000	Yes	MCC	25	47	18	5.8	(*N3)	# 0002	170.00			
6																					
7	COOPER iDP-210 SWGR	COOPER XFMR-N1	24.90	2.30	2.30	0.07	0.07	0.083	0.000	Yes	SWG	152	56	36	2.9	(*N11)		30.00			
8	COOPER iDP-210 SWGR	N2-M3520 (COOPER XFMR-N2)	24.90	2.30	2.30	0.18	0.18	0.083	0.000	Yes	SWG	152	56	36	2.9	(*N5) (*N11)		95.00			
9	COOPER iDP-210 SWGR	TXU-ST1	24.90	2.30	2.30	2.07	2.07	0.061	0.083	Yes	SWG	152	73	36	4.8	(*N11)	# 0004	1.00			
10	COOPER iDP-210 SWGR (iDP-210 LineSide)	iDP-210	24.90	2.30	2.30	0.25	0.25	0.083	0.000	Yes	SWG	152	56	36	2.9	(*N11)					
11	COOPER iDP-210 SWGR (iDP-210 LineSide)	TXU-ST1	24.90	2.30	2.30	2.07	2.07	0.061	0.083	Yes	SWG	152	73	36	4.8	(*N11)	# 0004-Line				
12																					
13	MCC-A-EAST	SR-369-2	4.16	5.49	5.38	0.45	0.44	0.083	0.000	Yes	SWG	104	14	36	0.48				0.48		
14	MCC-A-EAST	D1-MIF-II	4.16	5.49	5.38	5.04	4.94	0.017	0.083	Yes	SWG	104	17	36	0.57		# 0003	40.00	0.57		
15	MCC-A-EAST (400E-FUSE-1 LineSide)	SR-369-2 (400E-FUSE-1)	4.16	5.49	5.38	0.45	0.44	0.083	0.000	Yes	SWG	104	14	36	0.48	(*N5)			0.48		
16	MCC-A-EAST (400E-FUSE-1 LineSide)	D1-MIF-II	4.16	5.49	5.38	5.04	4.94	0.017	0.083	Yes	SWG	104	17	36	0.57		# 0006-Line		0.57		
17																					
18	MCC-B-WEST	SR-369-5	4.16	6.18	6.04	0.61	0.60	0.083	0.000	Yes	SWG	104	16	36	0.55				0.55		
19	MCC-B-WEST	SR-369-6	4.16	6.18	6.04	0.61	0.60	0.083	0.000	Yes	SWG	104	16	36	0.55				0.55		
20	MCC-B-WEST	D2-MIF-II	4.16	6.18	6.04	4.97	4.86	0.017	0.083	Yes	SWG	104	19	36	0.63		# 0008	40.00	0.63		
21	MCC-B-WEST (400E FUSE-2 LineSide)	400E FUSE-2	4.16	6.18	6.04	1.22	1.19	0.083	0.000	Yes	SWG	104	16	36	0.55				0.55		
22	MCC-B-WEST (400E FUSE-2 LineSide)	D2-MIF-II	4.16	6.18	6.04	4.97	4.86	0.017	0.083	Yes	SWG	104	19	36	0.63		# 0008-Line		0.63		
23																					
24	SWGR N1-EAST	SR-369-2 (D1-MIF-II)	4.16	5.50	5.39	0.45	0.44	0.083	0.000	Yes	SWG	104	14	36	0.49	(*N5)			0.49		
25	SWGR N1-EAST	N1-M3520	4.16	5.50	5.39	5.05	4.95	0.535	0.083	Yes	SWG	104	101	36	3.3		# 0012				
26	SWGR N1-EAST (N1-M3520 LineSide)	D1-MIF-II (N1-M3520)	4.16	5.50	5.39	0.45	0.44	0.083	0.000	Yes	SWG	104	14	36	0.49	(*N5)			0.49		

Attachment XV - Arc Flash Study Computer Output Report – Normal Operation

	Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Ground	Equip Type	Gap (mm)	Arc Flash Boundary (in)	Working Distance (in)	Incident Energy (cal/cm2)	PPE Level / Notes (*N)	Label #	Cable Length From Trip Device (ft)	Incident Energy at Low Marginal	Incident Energy at High Marginal	User Notes
27	SWGR N1-EAST (N1-M3520 LineSide)	TXU-ST1 (COOPER XFMR-N1)	4.16	5.50	5.39	4.67	4.58	0.062	0.083	Yes	SWG	104	24	36	0.81	(*N5)	# 0013-Line	526.00	0.81		
28																					
29	SWGR N2-WEST	D2-MIF-II	4.16	6.18	6.05	1.22	1.19	0.083	0.000	Yes	SWG	104	16	36	0.55				0.55		
30	SWGR N2-WEST	N2-M3520	4.16	6.18	6.05	4.97	4.87	0.55	0.083	Yes	SWG	104	105	36	3.4		# 0015				
31	SWGR N2-WEST (N2-M3520 LineSide)	D2-MIF-II (N2-M3520)	4.16	6.18	6.05	1.22	1.19	0.083	0.000	Yes	SWG	104	16	36	0.55	(*N5)			0.55		
32	SWGR N2-WEST (N2-M3520 LineSide)	TXU-ST1 (COOPER XFMR-N2)	4.16	6.18	6.05	4.97	4.87	0.062	0.083	Yes	SWG	104	26	36	0.87	(*N5)	# 0016-Line	506.00	0.87		
33	Level 1: Minimum of 4 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, and face shield or arc flash suit hood. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.	0.0 - 4.0 cal/cm^2													#Level 0 = 0	(*N11) - Out of IEEE 1584 Range, Lee Equation Used. Applicable for Open Air only. Existing Equipment type is not Open Air!					
34	Level 2: Minimum of 8 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, face shield or arc flash suit hood and balaclava. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.	4.0 - 8.0 cal/cm^2													#Level 1 = 8	(*N3) - Arcing Current Low Tolerances Used					
35	Level 3: Minimum of 25 cal/cm2 arc-rated clothing consisting of long-sleeve shirt, pants, coverall, flash suit jacket, flash suit pants, flash suit hood, arc-rated gloves. Hard hat, safety glasses/goggles, hearing protection, and leather footwear.	8.0 - 25.0 cal/cm^2													#Level 2 = 4	(*N5) - Miscoordinated, Upstream Device Tripped					

	Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Ground	Equip Type	Gap (mm)	Arc Flash Boundary (in)	Working Distance (in)	Incident Energy (cal/cm2)	PPE Level / Notes (*N)	Label #	Cable Length From Trip Device (ft)	Incident Energy at Low Marginal	Incident Energy at High Marginal	User Notes
36	Level 4: Minimum of 40 cal/cm2 arc-rated clothing consisting of long-sleeve shirt, pants, coverall, flash suit jacket, flash suit pants, flash suit hood, arc-rated gloves. Hard hat, safety glasses/goggles, hearing protection, and leather footwear.	25.0 - 40.0 cal/cm^2													#Level 3 = 0						
37	Level Dangerous!: No FR Category Found	40.0 - 999.0 cal/cm^2													#Level 4 = 0	NFPA 70E 2015 Annex D.4 - IEEE 1584 Bus + Line Side Report (Include Line Side + Load Side Contributions), - 80% Cleared Fault Threshold, include Ind. Motors for 5.0 Cycles), mis-coordination checked					
38															#Danger = 0						
39	For additional information refer to NFPA 70 E, Standard for Electrical Safety in the Workplace.														#Equip Eval Failed = 0						
40	Level 1: Minimum of 4 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, and face shield or arc flash suit hood. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear. , Hardhat + Polycarbonate Face Shield + Safety Glasses, Voltage Rated Electrical Gloves, Rubber Soled Leather Boots	Device with 80% Cleared Fault Threshold																			

	Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Ground	Equip Type	Gap (mm)	Arc Flash Boundary (in)	Working Distance (in)	Incident Energy (cal/cm2)	PPE Level / Notes (*N)	Label #	Cable Length From Trip Device (ft)	Incident Energy at Low Marginal	Incident Energy at High Marginal	User Notes
41	Level 2: Minimum of 8 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, face shield or arc flash suit hood and balaclava. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear., Hardhat + Polycarbonate Face Shield + Safety Glasses + Ear Canal Inserts, Voltage Rated Electrical Gloves, Rubber Soled Leather Boots																				
42	Level 3: Minimum of 25 cal/cm2 arc-rated clothing consisting of long-sleeve shirt, pants, coverall, flash suit jacket, flash suit pants, flash suit hood, arc-rated gloves. Hard hat, safety glasses/goggles, hearing protection, and leather footwear., Hardhat + Polycarbonate Face Shield + Safety Glasses + Ear Canal Inserts, Voltage Rated Electrical Gloves, Rubber Soled Leather Boots																				

	Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Ground	Equip Type	Gap (mm)	Arc Flash Boundary (in)	Working Distance (in)	Incident Energy (cal/cm2)	PPE Level / Notes (*N)	Label #	Cable Length From Trip Device (ft)	Incident Energy at Low Marginal	Incident Energy at High Marginal	User Notes
43	Level 4: Minimum of 40 cal/cm2 arc-rated clothing consisting of long-sleeve shirt, pants, coverall, flash suit jacket, flash suit pants, flash suit hood, arc-rated gloves. Hard hat, safety glasses/goggles, hearing protection, and leather footwear., Hardhat + Polycarbonate Face Shield + Safety Glasses + Ear Canal Inserts, Voltage Rated Electrical Gloves, Rubber Soled Leather Boots																				
44	Level Dangerous!: No FR Category Found, Do not work on live!																				
45																					

	Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Ground	Equip Type	Gap (mm)	Arc Flash Boundary (in)	Working Distance (in)	Incident Energy (cal/cm2)	PPE Level / Notes (*N)	Label #	Cable Length From Trip Device (ft)	Incident Energy at Low Marginal	Incident Energy at High Marginal	User Notes
1	480V MCC-CENTRAL	CS3-40E-FUSE-1	0.48	4.32	2.72	4.32	2.72	0.767	0.000	Yes	MCC	25	48	18	5.9	(*N3)	# 0002	170.00			
2																					
3	MCC-A-EAST	SR-369-2	4.16	4.25	4.19	0.45	0.45	0.083	0.000	Yes	SWG	104	11	36	0.37				0.37		
4	MCC-A-EAST	D1-MIF-II	4.16	4.25	4.19	3.80	3.74	0.017	0.083	Yes	SWG	104	12	36	0.41		# 0006	40.00	0.41		
5	MCC-A-EAST (400E-FUSE-1 LineSide)	SR-369-2 (400E-FUSE-1)	4.16	4.25	4.19	0.45	0.45	0.083	0.000	Yes	SWG	104	11	36	0.37	(*N5)			0.37		
6	MCC-A-EAST (400E-FUSE-1 LineSide)	D1-MIF-II	4.16	4.25	4.19	3.80	3.74	0.017	0.083	Yes	SWG	104	12	36	0.41		# 0003-Line		0.41		
7																					
8	MCC-B-WEST	SR-369-5	4.16	4.25	4.19	0.61	0.60	0.083	0.000	Yes	SWG	104	11	36	0.37				0.37		
9	MCC-B-WEST	SR-369-6	4.16	4.25	4.19	0.61	0.60	0.083	0.000	Yes	SWG	104	11	36	0.37				0.37		
10	MCC-B-WEST	D2-MIF-II	4.16	4.25	4.19	3.04	2.99	0.452	0.083	Yes	SWG	104	47	36	1.6		# 0008	40.00			
11	MCC-B-WEST (400E FUSE-2 LineSide)	400E FUSE-2	4.16	4.25	4.19	1.22	1.20	0.083	0.000	Yes	SWG	104	11	36	0.37				0.37		
12	MCC-B-WEST (400E FUSE-2 LineSide)	D2-MIF-II	4.16	4.25	4.19	3.04	2.99	0.452	0.083	Yes	SWG	104	47	36	1.6		# 0005-Line				
13																					
14	SWGR GEN	BT2-MIF-II	4.16	4.26	4.19	1.67	1.64	0.083	0.000	Yes	SWG	104	11	36	0.37			5.00	0.37		
15	SWGR GEN	G1-SR489	4.16	4.26	4.19	2.59	2.55	1.917	0.083	Yes	SWG	104	169	36	5.4	(*N9)	# 0010				
16	SWGR GEN (G1-SR489 LineSide)	BT2-MIF-II (G1-SR489)	4.16	4.26	4.19	1.67	1.64	0.083	0.000	Yes	SWG	104	11	36	0.37	(*N2) (*N5)		5.00	0.37		
17	SWGR GEN (G1-SR489 LineSide)	MaxTripTime @2.0s	4.16	4.26	4.19	2.59	2.57	2	0.000	Yes	SWG	104	169	36	5.4	(*N2) (*N9)	# 0007-Line				
18																					
19	SWGR N1-EAST	SR-369-2 (D1-MIF-II)	4.16	4.25	4.19	0.45	0.45	0.083	0.000	Yes	SWG	104	11	36	0.37	(*N5)			0.37		
20	SWGR N1-EAST	BT1-MIF-II	4.16	4.25	4.19	3.80	3.74	0.1	0.083	Yes	SWG	104	19	36	0.63		# 0013		0.63		
21	SWGR N1-EAST (BT1-MIF-II LineSide)	D1-MIF-II (BT1-MIF-II)	4.16	4.25	4.19	0.45	0.45	0.083	0.000	Yes	SWG	104	11	36	0.37	(*N5)			0.37		
22	SWGR N1-EAST (BT1-MIF-II LineSide)	D2-MIF-II	4.16	4.25	4.19	1.22	1.20	0.083	0.000	Yes	SWG	104	11	36	0.37				0.37		
23	SWGR N1-EAST (BT1-MIF-II LineSide)	BT2-MIF-II	4.16	4.25	4.19	2.59	2.55	1.917	0.083	Yes	SWG	104	169	36	5.4	(*N9)	# 0011				
24																					
25	SWGR N2-WEST	D1-MIF-II (BT1-MIF-II)	4.16	4.26	4.19	0.45	0.45	0.083	0.000	Yes	SWG	104	11	36	0.37	(*N5)		5.00	0.37		
26	SWGR N2-WEST	D2-MIF-II	4.16	4.26	4.19	1.22	1.20	0.083	0.000	Yes	SWG	104	11	36	0.37				0.37		
27	SWGR N2-WEST	BT2-MIF-II	4.16	4.26	4.19	2.59	2.55	1.917	0.083	Yes	SWG	104	169	36	5.4	(*N9)	# 0016				
28	SWGR N2-WEST (BT2-MIF-II LineSide)	BT2-MIF-II	4.16	4.26	4.19	1.67	1.64	0.083	0.000	Yes	SWG	104	11	36	0.37				0.37		
29	SWGR N2-WEST (BT2-MIF-II LineSide)	G1-SR489	4.16	4.26	4.19	2.59	2.55	1.917	0.083	Yes	SWG	104	169	36	5.4	(*N9)	# 0013				

Attachment XVI - Arc Flash Study Computer Output Report – Emergency Operation

	Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Ground	Equip Type	Gap (mm)	Arc Flash Boundary (in)	Working Distance (in)	Incident Energy (cal/cm2)	PPE Level / Notes (*N)	Label #	Cable Length From Trip Device (ft)	Incident Energy at Low Marginal	Incident Energy at High Marginal	User Notes
30	Level 1: Minimum of 4 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, and face shield or arc flash suit hood. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.	0.0 - 4.0 cal/cm^2													#Level 0 = 0	(*N2) < 80% Cleared Fault Threshold					
31	Level 2: Minimum of 8 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, face shield or arc flash suit hood and balaclava. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.	4.0 - 8.0 cal/cm^2													#Level 1 = 5	(*N3) - Arcing Current Low Tolerances Used					
32	Level 3: Minimum of 25 cal/cm2 arc-rated clothing consisting of long-sleeve shirt, pants, coverall, flash suit jacket, flash suit pants, flash suit hood, arc-rated gloves. Hard hat, safety glasses/goggles, hearing protection, and leather footwear.	8.0 - 25.0 cal/cm^2													#Level 2 = 6	(*N5) - Miscoordinated, Upstream Device Tripped					
33	Level 4: Minimum of 40 cal/cm2 arc-rated clothing consisting of long-sleeve shirt, pants, coverall, flash suit jacket, flash suit pants, flash suit hood, arc-rated gloves. Hard hat, safety glasses/goggles, hearing protection, and leather footwear.	25.0 - 40.0 cal/cm^2													#Level 3 = 0	(*N9) - Max Arcing Duration Reached					

	Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Ground	Equip Type	Gap (mm)	Arc Flash Boundary (in)	Working Distance (in)	Incident Energy (cal/cm2)	PPE Level / Notes (*N)	Label #	Cable Length From Trip Device (ft)	Incident Energy at Low Marginal	Incident Energy at High Marginal	User Notes
34	Level Dangerous!: No FR Category Found	40.0 - 999.0 cal/cm^2													#Level 4 = 0	NFPA 70E 2015 Annex D.4 - IEEE 1584 Bus + Line Side Report (Include Line Side + Load Side Contributions), - 80% Cleared Fault Threshold, include Ind. Motors for 5.0 Cycles), mis-coordination checked					
35															#Danger = 0						
36	For additional information refer to NFPA 70 E, Standard for Electrical Safety in the Workplace.														#Equip Eval Failed = 0						
37	Level 1: Minimum of 4 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, and face shield or arc flash suit hood. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear. , Hardhat + Polycarbonate Face Shield + Safety Glasses, Voltage Rated Electrical Gloves, Rubber Soled Leather Boots	Device with 80% Cleared Fault Threshold																			

	Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Ground	Equip Type	Gap (mm)	Arc Flash Boundary (in)	Working Distance (in)	Incident Energy (cal/cm2)	PPE Level / Notes (*N)	Label #	Cable Length From Trip Device (ft)	Incident Energy at Low Marginal	Incident Energy at High Marginal	User Notes
38	Level 2: Minimum of 8 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, face shield or arc flash suit hood and balaclava. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear., Hardhat + Polycarbonate Face Shield + Safety Glasses + Ear Canal Inserts, Voltage Rated Electrical Gloves, Rubber Soled Leather Boots																				
39	Level 3: Minimum of 25 cal/cm2 arc-rated clothing consisting of long-sleeve shirt, pants, coverall, flash suit jacket, flash suit pants, flash suit hood, arc-rated gloves. Hard hat, safety glasses/goggles, hearing protection, and leather footwear., Hardhat + Polycarbonate Face Shield + Safety Glasses + Ear Canal Inserts, Voltage Rated Electrical Gloves, Rubber Soled Leather Boots																				

	Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Ground	Equip Type	Gap (mm)	Arc Flash Boundary (in)	Working Distance (in)	Incident Energy (cal/cm2)	PPE Level / Notes (*N)	Label #	Cable Length From Trip Device (ft)	Incident Energy at Low Marginal	Incident Energy at High Marginal	User Notes
40	Level 4: Minimum of 40 cal/cm2 arc-rated clothing consisting of long-sleeve shirt, pants, coverall, flash suit jacket, flash suit pants, flash suit hood, arc-rated gloves. Hard hat, safety glasses/goggles, hearing protection, and leather footwear., Hardhat + Polycarbonate Face Shield + Safety Glasses + Ear Canal Inserts, Voltage Rated Electrical Gloves, Rubber Soled Leather Boots																				
41	Level Dangerous!: No FR Category Found, Do not work on live!																				
42																					

WARNING
Arc Flash and Shock Risk
Appropriate PPE Required

72 in	Flash Hazard Boundary
4.8 cal/cm^2	Flash Hazard at 36 in
Level 2	Minimum of 8 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, face shield or arc flash suit hood and balaclava. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.
24900 VAC	Shock Hazard when cover is removed
3	Glove Class
72 in	Limited Approach
31 in	Restricted Approach

2

BUS BOLTED FAULT	2.30 kA
BUS ARCING FAULT	2.30 kA

Location: **25KV SWGR EXISTING**

Warning: Changes in equipment settings or system configuration will invalidate the calculated values and PPE requirements

03/31/2015

WARNING
Arc Flash and Shock Risk
Appropriate PPE Required

73 in	Flash Hazard Boundary
4.8 cal/cm^2	Flash Hazard at 36 in
Level 2	Minimum of 8 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, face shield or arc flash suit hood and balaclava. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.
24900 VAC	Shock Hazard when cover is removed
3	Glove Class
72 in	Limited Approach
31 in	Restricted Approach

2

BUS BOLTED FAULT	2.30 kA
BUS ARCING FAULT	2.30 kA

Location: **COOPER iDP-210 SWGR**

Warning: Changes in equipment settings or system configuration will invalidate the calculated values and PPE requirements

03/31/2015

WARNING
Arc Flash and Shock Risk
Appropriate PPE Required

48 in	Flash Hazard Boundary
5.9 cal/cm^2	Flash Hazard at 18 in
Level 2	Minimum of 8 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, face shield or arc flash suit hood and balaclava. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.
480 VAC	Shock Hazard when cover is removed
00	Glove Class
42 in	Limited Approach
12 in	Restricted Approach

2

BUS BOLTED FAULT	4.32 kA
BUS ARCING FAULT	2.72 kA

Location: **480V MCC-CENTRAL**

Warning: Changes in equipment settings or system configuration will invalidate the calculated values and PPE requirements

03/31/2015

WARNING
Arc Flash and Shock Risk
Appropriate PPE Required

17 in	Flash Hazard Boundary
0.57 cal/cm^2	Flash Hazard at 36 in
Level 1	Minimum of 4 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, and face shield or arc flash suit hood. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.
4160 VAC	Shock Hazard when cover is removed
1	Glove Class
60 in	Limited Approach
26 in	Restricted Approach

1

BUS BOLTED FAULT	5.49 kA
BUS ARCING FAULT	5.38 kA

Location: **MCC-A-EAST**

Warning: Changes in equipment settings or system configuration will invalidate the calculated values and PPE requirements

03/31/2015

Attachment XVII – All Arc Flash Labels

WARNING
Arc Flash and Shock Risk
Appropriate PPE Required

47 in	Flash Hazard Boundary
1.6 cal/cm^2	Flash Hazard at 36 in
Level 1	Minimum of 4 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, and face shield or arc flash suit hood. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.
4160 VAC	Shock Hazard when cover is removed
1	Glove Class
60 in	Limited Approach
26 in	Restricted Approach

1

BUS BOLTED FAULT	4.25 kA
BUS ARCING FAULT	4.19 kA

Location: MCC-B-WEST

Warning: Changes in equipment settings or system configuration will invalidate the calculated values and PPE requirements
03/31/2015

WARNING
Arc Flash and Shock Risk
Appropriate PPE Required

169 in	Flash Hazard Boundary
5.4 cal/cm^2	Flash Hazard at 36 in
Level 2	Minimum of 8 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, face shield or arc flash suit hood and balaclava. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.
4160 VAC	Shock Hazard when cover is removed
1	Glove Class
60 in	Limited Approach
26 in	Restricted Approach

2

BUS BOLTED FAULT	4.25 kA
BUS ARCING FAULT	4.19 kA

Location: SWGR N1-EAST

Warning: Changes in equipment settings or system configuration will invalidate the calculated values and PPE requirements
03/31/2015

WARNING
Arc Flash and Shock Risk
Appropriate PPE Required

169 in	Flash Hazard Boundary
5.4 cal/cm^2	Flash Hazard at 36 in
Level 2	Minimum of 8 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, face shield or arc flash suit hood and balaclava. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.
4160 VAC	Shock Hazard when cover is removed
1	Glove Class
60 in	Limited Approach
26 in	Restricted Approach

2

BUS BOLTED FAULT	4.26 kA
BUS ARCING FAULT	4.19 kA

Location: SWGR GEN

Warning: Changes in equipment settings or system configuration will invalidate the calculated values and PPE requirements
03/31/2015

WARNING
Arc Flash and Shock Risk
Appropriate PPE Required

169 in	Flash Hazard Boundary
5.4 cal/cm^2	Flash Hazard at 36 in
Level 2	Minimum of 8 cal/cm2 arc-rated clothing consisting of long-sleeve shirt and pants or coverall, face shield or arc flash suit hood and balaclava. Hard hat, safety glasses/goggles, hearing protection, heavy-duty leather gloves, and leather footwear.
4160 VAC	Shock Hazard when cover is removed
1	Glove Class
60 in	Limited Approach
26 in	Restricted Approach

2

BUS BOLTED FAULT	4.26 kA
BUS ARCING FAULT	4.19 kA

Location: SWGR N2-WEST

Warning: Changes in equipment settings or system configuration will invalidate the calculated values and PPE requirements
03/31/2015

Per-Unit Method

3Ø Short Circuit Calculation Per-Unit Method*

The per-unit method is generally used for calculating short-circuit currents when the electrical system is more complex.

After establishing a one-line diagram of the system, proceed to the following calculations: **

Step 1. $\dagger PUX_{utility} = \frac{KVA_{base}}{S.C.\ KVA_{utility}}$

Step 2. $PUX_{trans} = \frac{(\%X^{\bullet})(KVA_{base})}{(100)(KVA_{trans})}$

$PUR_{trans} = \frac{(\%R^{\bullet})(KVA_{base})}{(100)(KVA_{trans})}$

Step 3. $PUX_{component\ (cable,\ switches,\ CT,\ bus)} = \frac{(X_{\Omega})(KVA_{base})}{(1000)(KV)^2}$

Step 4. $PUR_{component\ (cable,\ switches,\ CT,\ bus)} = \frac{(R_{\Omega})(KVA_{base})}{(1000)(KV)^2}$

Step 5. Next, total all per-unit **X** and all per-unit **R** in system to point of fault.

Step 6. Determine the per-unit impedance of the system by:

$$PUZ_{total} = \sqrt{(PUR_{total})^2 + (PUX_{total})^2}$$

Step 7. Calculate the symmetrical RMS short-circuit current at the point of fault.

$$I_{S.C.\ sym\ RMS} = \frac{KVA_{base}}{\sqrt{3}\ (KV)(PUZ_{total})}$$

Step 8. Determine the motor load. Add up the full load motor currents.(Whenever motor and lighting loads are considered, such as supplied by 4 wire, 208Y/120 and 480Y/277 volt 3 phase systems, the generally accepted procedure is to assume 50% motor load based on the full load current rating of the transformer.)

Step 9. The symmetrical motor contribution can be approximated by using an average multiplying factor associated with the motors in the system. This factor varies according to motor design and in this text may be chosen as 4 times motor full load current for approximate calculation purposes. To solve for the symmetrical motor contribution:

$$^{***}I_{sym\ motor\ contrib} = (4) \times (I_{full\ load\ motor})$$

Step 10. The total symmetrical short-circuit rms current is calculated as:

$$^{\bullet\bullet}I_{total\ S.C.\ sym\ RMS} = (I_{S.C.\ sym\ RMS}) + (I_{sym\ motor\ contrib})$$

Step 11. Determine X/R ratio of the system to the point of fault.

$$X/R_{ratio} = \frac{PUX_{total}}{PUR_{total}}$$

Step 12. From Table 8, Column $\mathbf{M_m}$, obtain the asymmetrical factor corresponding to the X/R ratio determined in Step 11. This multiplier will provide the worst case asymmetry occurring in the first 1/2 cycle. When the average 3-phase multiplier is desired use column $\mathbf{M_a}$.

Step 13. The asymmetrical RMS short-circuit current can be calculated as:

$$I_{S.C.\ asym\ RMS} = (I_{S.C.\ sym\ RMS}) \times (Asym\ Factor)$$

Step 14. The short-circuit current that the motor load can contribute is an asymmetrical current usually approximated as being equal to the locked rotor current of the motor.*** As a close approximation with a margin of safety use:

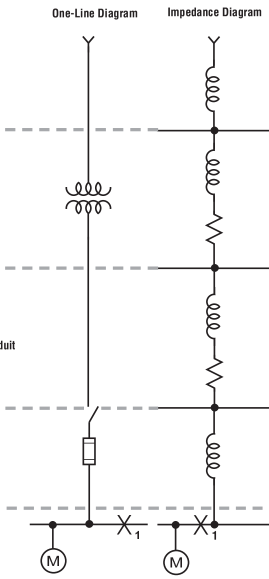
$$^{***}I_{asym\ motor\ contrib} = (5) \times (I_{full\ load\ motor})$$

Step 15. The total asymmetrical short-circuit RMS current is calculated as:

$$^{\bullet\bullet}I_{total\ S.C.\ asym\ RMS} = (I_{S.C.\ asym\ RMS}) + (I_{asym\ motor\ contrib})$$

* The base KVA used throughout this text will be 10,000 KVA.
** As in the ohmic method procedure, all ohmic values are single-phase distance one way, later compensated for in the three phase short-circuit formula by the factor, √3. (See Step 7.)
• UL Listed transformers 25KVA and larger have a ± 10% impedance tolerance. Short circuit amperes can be affected by this tolerance.
† Only per-unit X is considered in this procedure since utility X/R ratio is usually quite high. For more finite details obtain per-unit R of utility source.
*** A more exact determination depends upon the sub-transient reactance of the motors in question and associated circuit impedances. A less conservative method would involve the total motor circuit impedance to a common bus (sometimes referred to as a "zero reactance bus").
•• Arithmetical addition results in conservative values of fault current. More finite values involve vectorial addition of the currents.

Per-Unit Method – To Fault X_1 – System A



Component	Calculation	PUR (10,000 KVA Base)	PUX (10,000 KVA Base)
Available Utility S.C. MVA 100,000	$PUX = \frac{10,000}{100,000,000} = 0.0001$	—	0.0001
1500 KVA Transformer, 480V, 3Ø, 3.5%Z, 3.45%X, .56%R; $I_{f.l.\ trans}$ = 1804A	$PUX = \frac{(3.45)(10,000)}{(100)(1500)} = 0.2300$	—	0.2300
	$PUR = \frac{(.56)(10,000)}{(100)(1500)} = 0.0373$	0.0373	—
25' - 500kcmil 6 Per Phase Service Entrance Conductors in Steel Conduit	$PUX = \frac{\frac{(25')}{(1000)} \times \frac{(.0379)}{(6)} \times (10,000)}{(1000)(.480)^2} = 0.00685$	—	0.00685
	$PUR = \frac{\frac{(25')}{(1000)} \times \frac{(.0244)}{(6)} \times (10,000)}{(1000)(.480)^2} = 0.0044$	0.0044	—
2000A Switch; KRP-C-2000SP Fuse	$PUX = \frac{(.00005)(10,000)}{(1000)(.480)^2} = 0.00217$	—	0.00217
	Total PUR and PUX =	0.0417	0.2391

$PUZ_{total} = \sqrt{(0.0417)^2 + (0.2391)^2} = .2430$

$I_{S.C.\ sym\ RMS} = \frac{10,000}{\sqrt{3}\ (.480)(.2430)} = 49,489A$

$I_{sym\ motor\ contrib} = 4 \times 1804 = 7,216A$

$I_{total\ S.C.\ sym\ RMS\ (fault\ X_1)} = 49,489 + 7,216 = \underline{56,705A}$

$X/R_{ratio} = \frac{.2391}{.0417} = 5.73$

*Asym Factor = 1.294 (Table 8)

$I_{S.C.\ asym\ RMS} = 49,489 \times 1.294 = 64,039A$

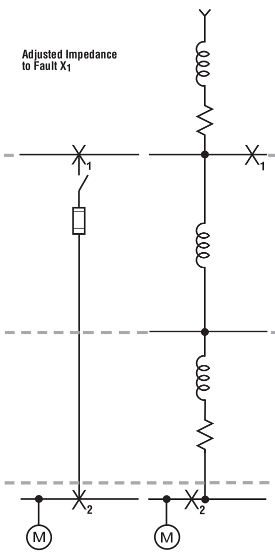
$I_{asym\ motor\ contrib\ (100\%\ motor\ load)} = 5 \times 1804 = 9,020A$

$I_{total\ S.C.\ asym\ RMS\ (fault\ X_1)} = 64,039 + 9,020 = \underline{73,059A}$

Note: See Per Unit Method Procedure for Formulas.
Actual motor contribution will be somewhat smaller than calculated due to impedance of the feeder cable.

Appendix I - Per Unit Method

Per-Unit Method – To Fault X_2 – System A



Component	Calculation	PUR (10,000 KVA Base)	PUX (10,000 KVA Base)
Adjusted Impedance to Fault X_1	PUX = .2391	—	.2391
	PUR = .0417	.0417	—
Fault X_1 / 400A Switch / LPS-RK400SP Fuse	$PUX = \frac{(.00008)(10,000)}{(1000)(.480)^2} = .0034$	—	.0034
50' - 500kcmil Feeder Cable in Steel Conduit	$PUX = \frac{\frac{50'}{1000} \times (.0379) \times (10,000)}{(1000)(.480)^2} = .0822$	—	.0822
	$PUR = \frac{\frac{50'}{1000} \times (.0244) \times (10,000)}{(1000)(.480)^2} = .0529$	.0529	—
Motor Contribution	Total PUR and PUX =	.0946	.3247

$PUZ_{total} = \sqrt{(.0946)^2 + (.3247)^2} = 0.3380$

$I_{S.C.\ sym\ RMS} = \frac{10,000}{\sqrt{3}\,(.480)(.3380)} = 35,621A$

$I_{sym\ motor\ contrib} = 4 \times 1804 = 7,216A$

$I_{total\ S.C.\ sym\ RMS\ (fault\ X_2)} = 35,621 + 7,216 = \underline{42,837A}$

$X/R_{ratio} = \frac{.32477}{.09465} = 3.43$

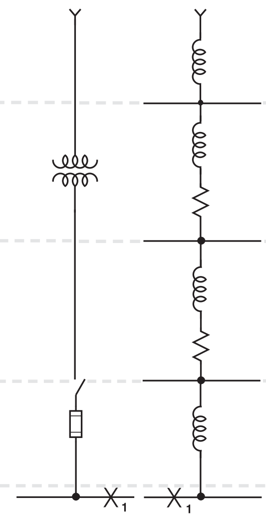
Asym Factor = 1.149 (Table 8)

$I_{S.C.\ asym\ RMS} = 1.149 \times 35,621 = 40,929A$

$I_{asym\ motor\ contrib\ (100\%motor\ load)} = 5 \times 1804 = 9,020A$

$I_{total\ S.C.\ asym\ RMS\ (fault\ X_2)} = 40,929 + 9,020 = \underline{49,949A}$

Per-Unit Method – To Fault X_1 – System B



Component	Calculation	PUR (10,000KVA Base)	PUX (10,000KVA Base)
Available Utility S.C. KVA 500,000	$PUX = \frac{10,000}{500,000} = .02$	—	.02
1000 KVA Transformer, 480V, 3Ø 3.45%X, .60%R	$PUX = \frac{(3.45)(10,000)}{(100)(1000)} = .345$	—	.345
	$PUR = \frac{(.6)(10,000)}{(100)(1000)} = .06$	.06	—
30' - 500kcmil 4 Per Phase Copper in PVC Conduit	$PUX = \frac{\frac{(30')}{(1000)} \times \frac{(.0303)}{(4)} \times (10,000)}{(1000)(.48)^2} = .0099$	—	.0099
	$PUR = \frac{\frac{(30')}{(1000)} \times \frac{(.0220)}{(4)} \times (10,000)}{(1000)(.48)^2} = .0072$	.0072	—
1600A Switch / KRP-C-1500SP Fuse	$PUX = \frac{(.00005)(10,000)}{(1000)(.48)^2} = .0022$	—	.0022
	Total PUR and PUX =	.0672	.3771

$PUZ_{total} = \sqrt{(.0672)^2 + (.3771)^2} = .383$

$I_{S.C.\ sym\ RMS} = \frac{10,000}{\sqrt{3}\,(.48)(.383)} = 31,405A$

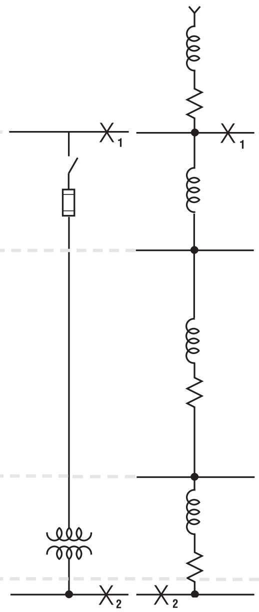
$X/R_{ratio} = \frac{.3771}{.0672} = 5.62$

Asym Factor = 1.285 (Table 8)

$I_{S.C.asym\ RMS} = 31,405 \times 1.285 = 40,355A$

Per-Unit Method – To Fault X_2 – System B

One-Line Diagram / Impedance Diagram



Component	Calculation	10,000 KVA PUR	10,000 KVA PUX
Adjusted Impedance to Fault X_1	$X_1 = .3771$	—	.3771
	$R_1 = .0672$	.0672	—
400A Switch LPS-RK-350SP Fuse	$PUX = \frac{(.00008)(10,000)}{(1000)(.48)^2} = .0035$	—	.0035
20' - 2/0 2 Per Phase Copper in PVC conduit	$PUX = \frac{\frac{(20')}{(1000)} \times \frac{(.0327)}{(2)} \times (10,000)}{(1000)(.48)^2} = .0142$	—	.0142
	$PUR = \frac{\frac{(20')}{(1000)} \times \frac{(.0812)}{(2)} \times (10,000)}{(1000)(.48)^2} = .0352$	.0352	—
225KVA Transformer, 208V, 3Ø .998%X, .666%R	$PUX = \frac{(.998)(10,000)}{(100)(225)} = .4435$	—	.4435
	$PUR = \frac{(.666)(10,000)}{(100)(225)} = .296$	.296	—
	Total PUR and PUX	.3984	.8383

$$PUZ_{total} = \sqrt{(.3984)^2 + (.8383)^2} = .928$$

$$I_{S.C.sym\ RMS} = \frac{10,000}{\sqrt{(3)}(.208)(.928)} = 29,911A$$

$$X/R_{ratio} = \frac{.8383}{.3984} = 2.10$$

Asym Factor = 1.0491 (Table 8)

$$I_{S.C.\ asym\ RMS} = 29,911 \times 1.0491 = 31,380A$$

PSA POWER SYSTEMS ANALYSIS

ELECTRICAL ENGINEERING
POWER SYSTEM STUDY
APPLICATION GUIDE

Fault Analysis
ANSI Method

Introduction

Performing short circuit calculations is a basic skill required of every electric power systems engineer. Engineers must be familiar with these calculation procedures, distribution equipment short circuit ratings and equipment short circuit test procedures to meet their professional responsibilities. The calculations are life-safety related and mandated per article 110.9 of the National Electrical Code.

The purpose of a short circuit calculation is twofold. First, to determine the maximum available RMS symmetrical current distribution equipment will be required to interrupt. Second, to determine the maximum peak current distribution equipment will be required to withstand.

Unfortunately, the electric power industry has complicated a relatively simple problem by changing standards and rating references every several years. This is why engineers must be familiar with current standards. Knowledge of how distribution equipment is rated and tested is critical. Distribution equipment such as fuses, LV circuit breakers, switchgear, switchboards, motor control centers and panelboards have only one published short circuit interrupting rating expressed in RMS symmetrical amperes. This rating is compared to the calculated maximum symmetrical current mentioned above. However, to complete the analysis, engineers must calculate an unpublished withstand rating in peak amperes. This rating is a function of the specified test circuit X/R ratio found in the applicable equipment standard. This calculated peak rating is compared to the calculated peak duty discussed above.

Calculation Methods and Assumptions

The short circuit problem can be solved using either steady state or dynamic analysis techniques. Algebraic equations are used to solve steady state problems in the areas of load flow, short circuit, motor starting and harmonics. Differential equations are used to solve dynamic problems such as motor starting, line switching, impact loading and fault clearing. This guide will cover the steady state solution process.

There are three industry accepted steady state solution methods, Classical, ANSI and IEC. The Classical method is defined in every first semester power systems analysis college textbook. The ANSI and IEC methods are defined in the ANSI/IEEE C37.010 and IEC-60909 standards respectively. All three methods assume that the fault impedance is zero, and that the system frequency and pre-fault voltages are constant. Shunt capacitors and pre-fault load flow currents are typically ignored.

The Classical and ANSI Methods are standard for 60hz distribution systems, while the IEC Method is standard for 50hz distribution systems. Further, in the US engineers responsible for low-voltage distribution systems more commonly use the Classical Method, while engineers responsible for medium-voltage distribution systems use the ANSI Method. The ANSI Method will be covered in this guide. The IEC and Classical Methods will not.

The Classical Method is characterized by developing an impedance network using rotating equipment subtransient reactances. The network is then reduced using Ohms' law to calculate the Thévenin equivalent fault impedance. It is standard practice to assume that the network impedances are constant for the duration of the fault, and that the pre-fault voltage is 1.0 per unit. Maximum peak and RMS symmetrical fault currents are then calculated and compared to equipment ratings.

In those cases where more accuracy is required, the Classical Method can be modified by separately analyzing a momentary impedance network and an interrupting impedance network. The momentary impedance network consists of rotating equipment subtransient reactances, and is applicable from time $0^+ < t < 1$ cycle after the fault. This network is used to calculate the RMS symmetrical and peak fault duties. The peak fault duties are compared to the peak ratings of all equipment. The RMS symmetrical duties are compared to low-voltage equipment ratings and medium-voltage fuse ratings. The interrupting impedance network consists of rotating equipment transient reactances, and is applicable from $2 < t < 8$ cycles after a fault. This network is used to calculate the RMS symmetrical interrupting fault duties. These duties are compared to interrupting ratings of medium-voltage equipment controlled by relays.

Another modification used to increase accuracy includes setting the pre-fault voltages equal to the calculated load flow voltages. This technique requires a separate load flow analysis for each short circuit configuration studied.

The ANSI Method is characterized by developing separate resistance and reactance diagrams for both the momentary and interrupting impedance networks. Each impedance diagram is reduced using Ohms' law to calculate the Thévenin equivalent fault resistance and reactance. The equivalent resistance and reactance are then combined to determine the total equivalent fault impedance. Note, it is not correct to separately reduce the resistance and reactance networks, however, the approach yields conservative results.

The momentary impedance network is developed using rotating equipment subtransient reactances. Fault point equivalent impedances are calculated and used to determine the peak fault duties. These duties are compared to the peak ratings of all equipment. The momentary network symmetrical duties are compared to low-voltage equipment ratings and medium-voltage fuse ratings.

The interrupting impedance network is developed using modified rotating equipment subtransient reactances. The reactances are modified to account for the change in reactance from the subtransient to the transient state. This network is applicable to medium-voltage equipment controlled by relays only. Fault point impedances are calculated and used to determine RMS symmetrical interrupting duties. Calculated duties are directly comparable to published interrupting ratings, as long as, the calculated X/R ratio is less than or equal to the short circuit test X/R ratio, as defined in the applicable equipment standard. If not, calculated interrupting duties are modified to determine minimum required equipment ratings.

Distribution Equipment Standards

Table 1. Distribution Equipment Short Circuit Test Data

Equipment	Test PF	Test X/R	S2P(1)	Standard
Low-Voltage Equipment				
Panelboards ≤ 10 kA	0.50	1.732	1.645	UL 67
10 kA < Panelboards ≤ 20 kA	0.30	3.180	1.941	UL 67
Panelboards > 20kA	0.20	4.899	2.159	UL 67
Motor Control Centers ≤ 10 kA	0.50	1.732	1.645	UL 845
10 kA < Motor Control Centers ≤ 20 kA	0.30	3.180	1.941	UL 845
Motor Control Centers > 20kA	0.20	4.899	2.159	UL 845
Switchboards ≤ 10 kA	0.50	1.732	1.645	UL 891
10 kA < Switchboards ≤ 20 kA	0.30	3.180	1.941	UL 891
Switchboards > 20kA	0.20	4.899	2.159	UL 891
Transfer Switches ≤ 10 kA	0.50	1.732	1.645	UL 1008
10 kA < Transfer Switches ≤ 20 kA	0.30	3.180	1.941	UL 1008
Transfer Switches > 20kA	0.20	4.899	2.159	UL 1008
Switchgear	0.15	6.591	2.292	ANSI C37.50
Molded Case Circuit Breakers ≤ 10 kA	0.50	1.732	1.645	UL 489
10 kA < Molded Case Circuit Breakers ≤ 20 kA	0.30	3.180	1.941	UL 489
Molded Case Circuit Breakers > 20kA	0.20	4.899	2.159	UL 489
Insulated Case Circuit Breakers ≤ 10 kA	0.50	1.732	1.645	UL 489
10 kA < Insulated Case Circuit Breakers ≤ 20 kA	0.30	3.180	1.941	UL 489
Insulated Case Circuit Breakers > 20kA	0.20	4.899	2.159	UL 489
Power Circuit Breakers	0.15	6.591	2.292	UL 1066
Fused Power Circuit Breakers	0.20	4.899	2.159	UL 1066
Fuses ≤ 10 kA	0.50	1.732	1.645	UL 248-1
Fuses > 10 kA	0.20	4.899	2.159	UL 248-1
HV/MV Equipment				
Switchgear (kA Rating Basis)	0.0587	17	2.590	ANSI C37.09-1999
Switchgear (MVA Rating Basis)	0.0665	15	2.561	ANSI C37.010-1979
E2 Motor Starter	0.0665	15	2.561	UL 347
Fuses	0.0665	15	2.561	ANSI C37.41

Notes:
1. The symmetrical-to-peak (S2P) factor is calculated using equation 12. The purpose of the S2P factor is to calculate the unpublished peak rating the equipment would carry according to the short circuit test procedures outlined in the applicable equipment standard. The unpublished peak rating would be calculated using equation 13.

Equations

$$R = Z / (1 + X/R^2)^{1/2} \quad (1)$$

$$X = R\,(X/R) \quad (2)$$

$$Z_{new} = Z_{old}\,[V_{old} / V_{new}]^2\,[S_{new} / S_{old}] \quad (3)$$

$$R = X / (X/R) \quad (4)$$

$$I_{3\Phi} = I_{base}\,(V_f / Z_f) \quad (5)$$

$$X/R = \tan\theta \quad (6)$$

$$I_{PEAK\ @\ ½\ cycle} = \sqrt{2}\,(1 + e^{-\Pi/(X/R)})\,I_{SYM} \quad (7)$$

$$I_{ASYM\ @\ ½\ cycle} = I_{SYM}\,(1+2e^{-2\Pi/(X/R)})^{1/2} \quad (8)$$

$$NACD = I_{remote} / I_{total} \quad (9)$$

$$I_{Rating} = MF\,(I_{Int\ Duty}) \quad (10)$$

$$SC_{rating\ new} = SC_{rating\ old}\,(V_{max}/V_{operating}) \quad (11)$$

$$S2P = I_{PEAK} / I_{SYM} = \sqrt{2}\,(1 + e^{-\Pi/(X/R)}) \quad (12)$$

$$I_{PEAK} = I_{SYM\ RTG} * S2P \quad (13)$$

ANSI Calculation Procedure

Step	Description	Equations
1	Select Base Quantities	-
2	Convert Impedances to Common Base	1, 2, 3, 4
3	Calculate Momentary Network Fault Impedance	-
4	Calculate Symmetrical Duty	5
5	Calculate Peak Duty	6, 7, 8
6	Adjust Machine Reactances	-
7	Calculate Interrupting Network Fault Impedance	-
8	Calculate Symmetrical Duty	5
9	Determine Type of Contribution and Multiplying Factors	6
10	Determine Required Rating	9, 10, 11

Problem - ANSI Calculation

Determine short circuit equipment ratings for medium-voltage switchgear applied on the 4.16kV system shown in Figure 1.

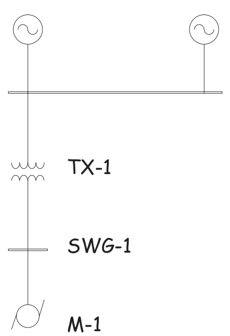


Fig. 1. Single line diagram.

Input Data

G-1

13.8kV, 20MVA, Xd″ = 0.1 Ω p.u., X/R = 50

G-2

13.8kV, 20MVA, Xd″ = 0.0999 Ω p.u., X/R = 50

TX-1

20MVA, 13.8-4.16kV, Δ-YG, Z = 15%, X/R = 50

M-1

Induction, 500KVA, 4kV, Xd″ = 0.16 Ω p.u., X/R = 50

Solution

Step 1 – Select Base Quantities

S_{base} = 20MVA

V_{base} = 4.16kV

$I_{base} = S_{base}/(\sqrt{3}\ V_{base})$ kA = 20MVA/(1.732 x 4.16kV) kA = 2.776kA

Step 2 - Convert Impedances to Common Base

X_{G-1} = 0.1001 Ω p.u.

X_{G-2} = 0.0999 Ω p.u.

From (1)

X_{M-1} = 0.16 Ω p.u. $[4.00kV/4.16kV]^2$[20MVA/0.5MVA] = 5.9172 Ω p.u.

From (2)

R_{TX-1} = 0.15 Ω p.u. / $(1 + 50^2)^{1/2}$= 0.0030 Ω p.u.

From (3)

$R_{M-1} = X_{M-1}/50$ = 0.1183 Ω p.u.

$R_{G-1} = X_{G-1}/50$ = 0.0020 Ω p.u.

$R_{G-2} = X_{G-2}/50$ = 0.0020 Ω p.u.

From (4)

$X_{TX-1} = R_{TX-1}$ (50) = 0.1500 Ω p.u.

Step 3 - Calculate Momentary Network Fault Impedance

Note, ANSI method allows engineer to build separate resistance and reactance networks.

$R_1 = (R_{G-1} \parallel R_{G-2} + R_{TX-1}) \parallel R_{M-1}$

$R_1 = 0.0039\ \Omega$ p.u.

$X_1 = (X_{G-1} \parallel X_{G-2} + X_{TX-1}) \parallel X_{M-1}$

$X_1 = 0.1934\ \Omega$ p.u.

$Z_1 = 0.1934\ \underline{/88.84^\circ}\ \Omega$ p.u.

Step 4 – Calculate Symmetrical Duty using (5)

$I_{3\Phi} = I_{base} V_f / Z_1$

$I_{3\Phi} = 2.776 \times 1.0 / 0.1934$ kA

$I_{3\Phi} = 14.4$kA

Step 5 – Calculate Peak Duty

From (6)

$X/R = \tan\theta$

$X/R = \tan(88.84^\circ) = 49.4$

For new equipment calculate the peak current according to ANSI C37.06-1997.

From (7)

$I_{PEAK} = \sqrt{2} * I_{SYM}(1 + e^{-\Pi/(X/R)})$

$I_{PEAK} = \sqrt{2} * 14.4kA\ (1 + e^{-\Pi/(49.4)}) = 39.5kA$

For existing equipment rated on an MVA basis, calculate the RMS asymmetrical current according to ANSI C37.06-1987.

From (8)

$I_{ASYM} = I_{SYM}(1+2e^{-2\Pi/(X/R)})^{1/2}$

$I_{ASYM} = 14.4kA\ (1+2e^{-2\Pi/(49.4)})^{1/2} = 23.9kA$

Step 6 – Adjust Machine Reactances

Only the induction motor impedance needs to be adjusted. The adjustment factor is 1.5 from Figure 2. Note, the figure lists reactance factors only. However, the standard applies the factors to both the resistance and reactance. This mistake has unfortunately been carried over throughout the years.

Type of rotating machine	Positive sequence reactances for calculating	
	Interrupting duty (per unit)	Closing and latching duty (per unit)
All turbo-generators, all hydro-generators with amortisseur windings, and all condensers[a]	$1.0\,X''_d$	$1.0\,X''_d$
Hydro-generators without amortisseur windings[a]	$0.75X'_d$	$0.75X'_d$
All synchronous motors[b,d,e]	$1.5\,X''_d$	$1.0\,X''_d$
Induction motors[c,d,e]		
Above 1000 hp at 1800 r/min or less Above 250 hp at 3,600 r/min	$1.5\,X''_d$	$1.0\,X''_d$
From 50 hp to 1000 hp at 1800 r/min or less From 50 hp to 250 hp at 3,600 r/min	$3.0\,X''_d$	$1.2\,X''_d$
Neglect all three-phase induction motors below 50 hp and all single-phase motors		

Fig. 2. Reactance multiplying factors.

The new motor impedances are:

$R_{M-1} = 1.5\ (0.1183)\ \Omega$ p.u.

$R_{M-1} = 0.1775\ \Omega$ p.u.

$X_{M-1} = 1.5\ (5.9172)\ \Omega$ p.u.

$X_{M-1} = 8.8758\ \Omega$ p.u.

Step 7 - Calculate Interrupting Network Fault Impedance

$R_1 = (R_{G-1} \,||\, R_{G-2} + R_{TX-1}) \,||\, R_{M-1}$

$R_1 = 0.0039\ \Omega$ p.u.

$X_1 = (X_{G-1} \,||\, X_{G-2} + X_{TX-1}) \,||\, X_{M-1}$

$X_1 = 0.1956\ \Omega$ p.u.

$Z_1 = 0.1956\ \underline{/88.86^\circ}\ \Omega$ p.u.

Step 8 – Calculate Symmetrical Duty

From (5)

$I_{3\Phi} = I_{base}\ V_f\ /\ Z_1$

$I_{3\Phi} = 2.776 \times 1.0\ /\ 0.1956$ kA

$I_{3\Phi} = 14.2$kA

Step 9 – Determine Type of Contribution and Multiplying Factors

First, determine if the generator contribution is local or remote. The contribution is considered remote if one of the following is true.

- The contribution is through two or more transformations.
- The contribution is in series with an external reactance ≧ 1.5 times the generator reactance.

Both generators are less than two transformations away from the fault. Therefore, must check impedance ratios.

G-1 Ratio = $X_{T\text{-}1}/X_{G\text{-}1}$ = 0.1500/0.1001 = 1.4985 ∴ local source

G-2 Ratio = $X_{T\text{-}1}/X_{G\text{-}2}$ = 0.1500/0.0999 = 1.5015 ∴ remote source

Next, determine the X/R ratio.

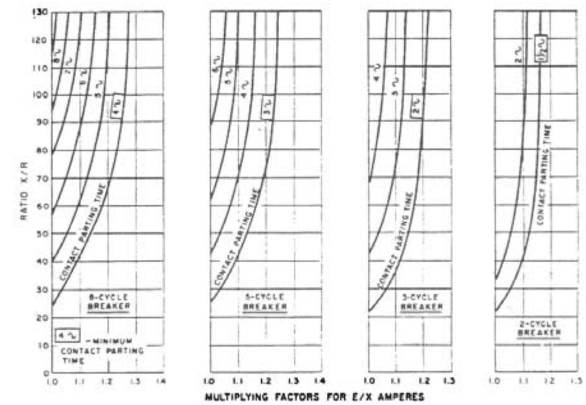
From (6)

$X/R = \tan\theta = \tan(88.86°) = 50$

Then, determine multiplying factors from Figure 3 (local) and 4 (remote) of ANSI C37.010-1999, assuming a 5-cycle breaker, with a 3-cycle contact-parting time and a circuit X/R ratio of 50.

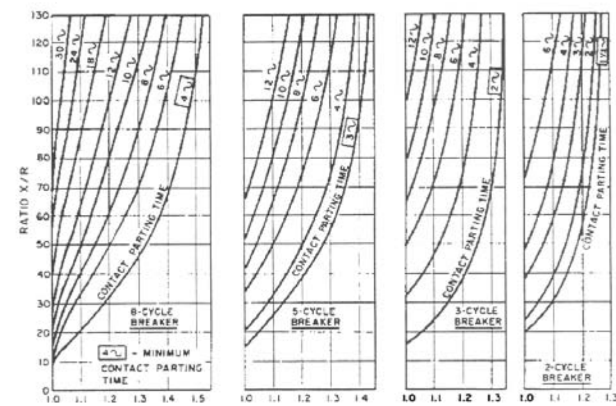
$MF_{local} \approx 1.13$

$MF_{remote} \approx 1.275$



Three-phase fault multiplying factors that include effects of ac and dc decrement [see 6.3.2 a)]

Fig. 3. Local multiplying factors.



-Three-phase and line-to-ground fault multiplying factors that include effects of dc decrement only [see 6.3.2 b)]

Fig. 4. Remote multiplying factors.

Step 10 – Determine Required Rating

Determine the total remote contribution.

I_{TOTAL} = 14.2kA

$I_{M-1} = I_{base}/X_{M-1}$ = 2.776kA/8.8758 Ω p.u. = 0.313

$I_{G-1+G-2}$ = 14.2 – 0.313 = 13.887kA

I_{G-1} = 13.887kA $[X_{G-2}/(X_{G-1} + X_{G-2})]$ = 6.937kA

I_{G-2} = 6.950kA

Calculate the NACD ratio from (9)

NACD = I_{remote}/I_{total}

NACD = 6.950kA/14.2kA = 0.4894

The required breaker rating is calculated from (10). Note motor contribution can be treated as either local or remote per IEEE Std 141-1993, page 154, paragraph 1. The conservative approach is to consider all motor contribution remote.

$I_{Rating} = MF\,(I_{Int\ Duty})$

$I_{Rating} = MF_{local}\,(I_{G-1}) + MF_{remote}\,(I_{M-1} + I_{G-2})$

I_{Rating} = 1.13 x 6.937kA + 1.275 (0.313kA + 6.950kA)

I_{Rating} = 17.1kA

If purchasing new switchgear ANSI C37.06-1997 applies.

Table 2. ANSI C37.06-1997 Results.

Rated Voltage kV	Rated SC Current kA, RMS Sym	Rated Close & Latch kA, Peak	Calculated SC Rating kA, RMS Sym	Calculated C&L Duty kA, Peak
→ 4.76	31.5	82	17.1 (54%)	39.5 (48%) ←
4.76	40	104	17.1 (43%)	39.5 (38%)
4.76	50	130	17.1 (34%)	39.5 (30%)

If evaluating existing switchgear rated on an MVA basis, ANSI C37.06-1987 applies. The 1987 standard required SC current ratings to be adjusted for the operating voltage using (11).

$SC_{rating\ new} = SC_{rating\ old}\,(V_{max}/V_{operating})$

$SC_{250MVA\ rating}$ = 29kA(4.76kV/4.16kV) = 33.2kA

$SC_{350MVA\ rating}$ = 41kA(4.76kV/4.16kV) = 46.9kA

Table 3. ANSI C37.06-1987 Results.

Rated Voltage KV-MVA	Rated/Adj SC Current kA, RMS Sym	Rated Close & Latch kA, RMS	Calculated SC Rating kA, RMS Sym	Calculated C&L Duty kA, RMS
→ 4.76-250	29/33.2	58	17.1 (52%)	23.9 (41%) ←
4.76-350	41/46.9	78	17.1 (36%)	23.9 (31%)

In either case, the minimum switchgear ratings available would be sufficient for the application.

About the Author

Tom Smith holds Bachelors degrees in Electrical Engineering and Education from the University of Nebraska and is a registered Professional Engineer. He began his career at the U.S. Army Corps of Engineers Omaha District in 1983. He joined the Reading offices of Gilbert /Commonwealth in 1988. He has served as a consulting engineer since 1995.

His experience includes the design and analysis of commercial, industrial and utility electrical distribution systems. He also teaches several courses in load flow, motor starting, short circuit, overcurrent coordination and arc flash.

PSA

BICE Engineering and Consulting

Typical Information Required For Arc-Flash Hazard Analysis:

1. **Utility or Local Energy Provider:** Thevenin Impedance in Ohms or In Per Unit on 100 MVA base; **or** 3-Phase and SLG MVA_{sc} available and X/R; **or** 3-Phase and SLG I_{sc} available and X/R ratio.
2. **Electrical conductors:** Type (i.e., CU/AL Cable, Segregated Bus Duct, Cable Bus, Isolated Phase Bus Duct, etc…), Size, Ampere Rating, length (ft), Insulation Type, Number of Conductors Per Phase, and Voltage Rating.
3. **Molded Case Circuit Breakers:** Manufacturer, Type/Model, Continuous Ampere Rating, Voltage Rating, Short Circuit Current Interrupting Rating, and Instantaneous Trip Setting (If available).
4. **Circuit Breakers w/ Electronic Static Trip Units:** Manufacturer, Type, Continuous Ampere Frame Rating, LTPU, LTD, STP, STD, INST, and GF Settings. Also, provide breaker short circuit current interrupting rating.
5. **Protective Relays:** Manufacturer, Model/Type, CT ratio, Tap Setting, Time Dial Setting, Instantaneous Trip Setting.
6. **Fuses:** Manufacturer, Type, Continuous Amp Rating, Short Circuit Current Interrupting Rating, Voltage Rating.
7. **Transformers:** MVA or KVA rating, Primary-Secondary Winding Configuration and Voltages, Neutral Grounding Resistor Rating (If Used), X/R ratio, and Percent Impedance (%Z) on Nominal MVA or KVA base.
8. **AC Induction Motors:** Rated Hp, Voltage, Full Load Amperes, Power Factor, Efficiency, Number of Poles, Rated Synchronous Speed (RPM).
9. **Synchronous Generators:** Base MVA or KVA Rating, Output Voltage, Synchronous Speed or Output Frequency (Hz), Number of Poles, Saturated Synchronous Reactance (Xd_v), Saturated Transient Reactance ($X'd_v$), Saturated Subtransient Reactance ($X''d_v$), Transient Time Constant (Td'), Subtransient Time Constant (Td"), and Armature Short Circuit Time Constant (Ta).
10. **Switchboards, Motor Control Centers, Panelboards, Switchgear:** Manufacturer, Model/Type, Voltage Rating, Continuous Ampere Rating, Number of Phases, Number of Wires, Rated Frequency, and Short Circuit Current Bus Bracing Rating.

5. Model for incident energy calculations

An empirically derived model is provided to enable calculations. Development of this model is discussed in Clause 9. Software programs for applying the model are discussed in Clause 6 and Annex B, and also presented in the auxiliary files. [12] The equations in the model are embedded in the spreadsheet, because it is impractical to solve them by hand.

5.1 Ranges of models

The empirically derived model (see 7.5 and Clause 9), based upon statistical analysis and curve fitting programs, is applicable for systems with

- Voltages in the range of 208 V–15 000 V, three-phase.
- Frequencies of 50 Hz or 60 Hz.
- Bolted fault current in the range of 700 A–106 000 A.
- Grounding of all types and ungrounded.
- Equipment enclosures of commonly available sizes.
- Gaps between conductors of 13 mm–152 mm.
- Faults involving three phases.

A theoretically derived model, based upon Lee's paper [B19], is applicable for three-phase systems in open air substations, and open air transmission and distribution systems. This model is intended for applications where faults will escalate to three-phase faults. Where this is not possible or likely, this model will give a conservative result. Where single-phase systems are encountered, this model will provide conservative results.

5.2 Arcing current

The predicted three-phase arcing current must be found so the operating time for protective devices can be determined.

For applications with a system voltage under 1000 V solve the equation (1):

$$\lg I_a = K + 0.662 \lg I_{bf} + 0.0966\, V + 0.000526\, G + 0.5588\, V (\lg I_{bf}) - 0.00304\, G (\lg I_{bf}) \quad (1)$$

where

- lg is the $\log_{10}$
- I_a is arcing current (kA)
- K is –0.153 for open configurations and is –0.097 for box configurations
- I_{bf} is bolted fault current for three-phase faults (symmetrical RMS) (kA)
- V is system voltage (kV)
- G is the gap between conductors, (mm) (see Table 4)

For applications with a system voltage of 1000 V and higher solve the equation (2):

$$\lg I_a = 0.00402 + 0.983 \lg I_{bf} \quad (2)$$

The high-voltage case makes no distinction between open and box configurations.

[12] See Footnote 1

Convert from lg:

$$I_a = 10^{\lg I_a} \quad (3)$$

Calculate a second arc current equal to 85% of I_a, so that a second arc duration can be determined (see 9.10.4).

5.3 Incident energy

First find the $\log_{10}$ of the incident energy normalized. This equation is based on data normalized for an arc time of 0.2 seconds and a distance from the possible arc point to the person of 610 mm.

$$\lg E_n = K_1 + K_2 + 1.081 \lg I_a + 0.0011\, G \quad (4)$$

where

- E_n is incident energy (J/cm^2) normalized for time and distance [13]
- K_1 is –0.792 for open configurations (no enclosure) and is –0.555 for box configurations (enclosed equipment)
- K_2 is 0 for ungrounded and high-resistance grounded systems and is –0.113 for grounded systems
- G is the gap between conductors (mm) (see Table 4)

Then:

$$E_n = 10^{\lg E_n} \quad (5)$$

Finally, convert from normalized:[14]

$$E = 4.184\, C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{610^x}{D^x}\right) \quad (6)$$

where

- E is incident energy (J/cm^2)
- C_f is a calculation factor
  1.0 for voltages above 1kV, and
  1.5 for voltages at or below 1kV
- E_n is incident energy normalized [15]
- t is arcing time (seconds)
- D is distance from the possible arc point to the person (mm)
- x is the distance exponent from Table 4.

The other cases are handled similarly.

[13] Measurement utilized in test laboratories was cal/cm^2.
[14] See E.3.1 for calculation using cal/cm^2.
[15] See Footnote 1.

Appendix IV - Section 5 of IEEE 1584-2002

Table 4—Factors for equipment and voltage classes[a]

System voltage (kV)	Equipment type	Typical gap between conductors (mm)	Distance x factor
0.208–1	Open air	10–40	2.000
	Switchgear	32	1.473
	MCC and panels	25	1.641
	Cable	13	2.000
>1– 5	Open air	102	2.000
	Switchgear	13–102	0.973
	Cable	13	2.000
>5–15	Open air	13–153	2.000
	Switchgear	153	0.973
	Cable	13	2.000

[a]The distance x factor is used in 5.3 as an exponent.

5.4 Lee method

For cases where voltage is over 15 kV, or gap is outside the range of the model, the theoretically derived Lee method can be applied and it is included in the IEEE Std 1584-2002 Incident Energy Calculators.[16] See 7.2 and 9.11.4.

$$E = 2.142 \times 10^6 V I_{bf}\left(\frac{t}{D^2}\right) \tag{7}$$

where[17]

- E is incident energy (J/cm^2)
- V is system voltage (kV)
- t is arcing time (seconds)
- D is distance from possible arc point to person (mm)
- I_{bf} is bolted fault current

For voltages over 15 kV, arc fault current is considered to be equal to the bolted fault current.

5.5 Flash-protection boundary

For the IEEE Std 1584-2002 empirically derived model: [18]

$$D_B = \left[4.184 C_f E_n\left(\frac{t}{0.2}\right)\left(\frac{610^x}{E_B}\right)\right]^{\frac{1}{x}} \tag{8}$$

For the Lee method: [19]

$$D_B = \sqrt{2.142 \times 10^6 V I_{bf}\left(\frac{t}{E_B}\right)} \tag{9}$$

where

- D_B is the distance of the boundary from the arcing point (mm)
- C_f is a calculation factor
  1.0 for voltages above 1 kV, and
  1.5 for voltages at or below 1 kV,
- E_n is incident energy normalized[20]
- E_B is incident energy in J/cm^2 at the boundary distance
- t is time (seconds)
- x is the distance exponent from Table 4.
- I_{bf} is bolted fault current

E_B can be set at 5.0 J/cm^2 for bare skin (no hood) or at the rating of proposed PPE.[21]

5.6 Current limiting fuses

Formulae for calculating arc-flash energies for use with current-limiting Class L and Class RK1 fuses have been developed. These formulae were developed based upon testing at 600 V and a distance of 455 mm using one manufacturer's fuses. The variables are as follows:

- I_{bf} is bolted fault current for three-phase faults (symmetrical RMS) (kA)
- E is incident energy (J/cm^2).

5.6.1 Equations for Class L fuses 1601 A–2000 A

For $I_{bf} < 22.6$ kA, calculate arcing current and use time-current curves to determine energy per 5.2 and 5.3:

For I_{bf}, such that $22.6 \text{ kA} \le I_{bf} \le 65.9$ kA,

$$E = 4.184\,(-0.1284\,I_{bf} + 32.262) \tag{10}$$

For I_{bf}, such that $65.9 \text{ kA} < I_{bf} \le 106$ kA,

$$E = 4.184(-0.5177\,I_{bf} + 57.917) \tag{11}$$

For $I_{bf} > 106$ kA, contact manufacturer for information.

5.6.2 Equations for Class L fuses 1201 A–1600 A

For $I_{bf} < 15.7$ kA, calculate arcing current and use time-current curves to determine energy per 5.2 and 5.3:

For I_{bf}, such that $15.7 \text{ kA} \le I_{bf} \le 31.8$ kA,

$$E = 4.184\,(-0.1863\,I_{bf} + 27.926) \tag{12}$$

[16]See Footnote 1.
[17]See Footnote 14.
[18]See Footnote 14.
[19]See Footnote 14.
[20]See Footnote 13.
[21]5.0 J/cm^2 = 1.2 cal/cm^2

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PSA POWER SYSTEMS ANALYSIS

ELECTRICAL ENGINEERING
POWER SYSTEM STUDY
APPLICATION GUIDE

Arc Flash Analysis
IEEE 1584 Method

Introduction

Performing arc flash calculations is a new skill required of every electric power systems engineer. The calculations are life-safety related and mandated per article 110.16 of the National Electrical Code. There are two industry accepted solution methods, NFPA 70E and IEEE 1584. The IEEE 1584 Method will be covered in this guide.

The primary purpose an arc flash study is to determine and label the maximum incident energy available at every location along the distribution network likely to require examination, adjustment, servicing or maintenance. Knowing the available incident energy allows workers to select the proper protective clothing for the application. Another purpose is to determine the arc flash boundary distance that must be maintained by unprotected workers. The arc flash boundary is the distance at which the incident energy drops to 1.2 cal/cm^2 (5.0 J/cm^2). This represents the energy limit for a second-degree bare skin burn.

Arc Flash Study Input Data Requirements

One Line Diagram:	Up-to-date Single Line Diagram
Fault Study Results:	Maximum Fault Currents
OC Study Results:	Device Fault Clearing Times

Equations

Applicable for systems with

- Voltages $\geq$ 208V
- Frequencies of 50Hz or 60Hz
- Bolted three-phase fault current in the range of 700A – 106,000A
- Grounding of all types
- Equipment enclosures of commonly available sizes
- Conductor gaps of 13mm – 152mm

Arcing Current

For bus voltages 208V $\leq$ V $\leq$ 1kV

$$I_a = 10^{(K + 0.662B + 0.0966V + 0.000526G + 0.5588V(B) - 0.00304G(B))} \quad (1)$$

For bus voltages 1kV < V $\leq$15kV

$$I_a = 10^{(0.00402 + 0.983B)} \quad (2)$$

For bus voltages V > 15kV (Lee Method)

$$I_a = I_{bf} \quad (3)$$

Incident Energy

For bus voltages $208V \leq V \leq 15kV$

$$E = 4.184C_f(10^{(K1 + K2 + 1.081C + 0.0011G)})(t/0.2)(610/D)^x \quad (4)$$

For bus voltages V > 15kV (Lee Method)

$$E = 2.142x10^6 \; V \; I_{bf} \; (t/D^2) \quad (5)$$

Arc Flash Boundary Distance

For bus voltages $208V \leq V \leq 15kV$

$$D_B = [4.184C_f(10^{(K1 + K2 + 1.081C + 0.0011G)})(t/0.2)(610^x/5)]^{1/x} \quad (6)$$

For bus voltages V > 15kV (Lee Method)

$$D_B = 2.142x10^6 \; V \; I_{bf} \; (t/25) \quad (7)$$

Terms

I_a = arcing fault current, kA

I_{bf} = maximum bolted three-phase fault current, kA

K = -0.153 for open configurations (no enclosure)

-0.097 for box configurations (enclosed equipment)

B = $\log_{10}(I_{bf})$

C = $\log_{10}(I_a)$

V = bus voltage, kV

G = gap between conductors, mm (Table 1)

E = Incident Energy, J/cm^2

C_f = 1.0 for voltages above 1kV

1.5 for voltages at or below 1kV

K1 = -0.792 for open configurations

-0.555 for box configurations

K2 = 0 for ungrounded and high-resistance grounded systems

-0.113 for grounded systems

t = arcing time, seconds

D = working distance, mm (Table 2)

D_B = arc flash boundary distance, mm

x = distance exponent (Table 3)

Table 1 Typical Equipment Bus Gaps

Class of Equipment	Typical Bus Gaps (mm)
15kV Equipment	152
5kV Equipment	104
LV Switchgear	32
LV MCCs & Panelboards	25
Cable	13

Table 2 Typical Equipment Working Distances

Class of Equipment	Typical Working Distance (mm)
15kV Equipment	910
5kV Equipment	910
LV Switchgear	610
LV MCCs & Panelboards	455
Cable	455

Table 3 Distance Factor Exponents

System Voltages (kV)	Equipment Type	Typical Conductor Gaps (mm)	Distance Factor
0.208 – 1	Open Air	10-40	2.000
	Switchgear	32	1.473
	MCCs and Panels	25	1.641
	Cable	13	2.000
> 1 – 5	Open Air	102	2.000
	Switchgear	12-102	0.973
	Cable	13	2.000
> 5 – 15	Open Air	13-153	2.000
	Switchgear	153	0.973
	Cable	13	2.000

Calculation Procedure

Step	Description	Equations
1	Calculate I_{arc}	1, 2, 3
2	Determine Fault Clearing Time from TCC	-
3	Calculate Incident Energy	4, 5
4	Determine Clothing Class	-
5	Calculate Arc Flash Boundary	6, 7

Problem 1 – LV MCC

Determine the protective clothing requirements for maintenance personnel working on the energized 480V *MCC* of Figure 1.

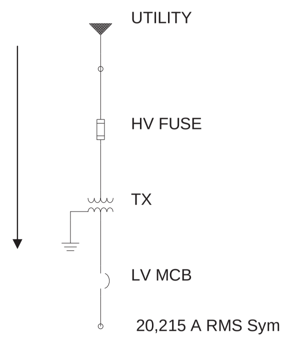


Fig. 1 Single Line Diagram

Input Data

Utility

13.8kV, 500MVA, X/R=8

HV Fuse

GE, EJO-1, 100E

TX

1000kVA, 13.8kV-480V, 5.75%, X/R=10

LV MCB

GE, TKL, 1200AP, LTPU=1, LTD=2, STPU=5, STD=MIN, I2T = In, INST=15

Solution

Step 1 – Calculate the *Arc Current* at the 480V *MCC* using (1)

$I_a = 10^{(K + 0.662B + 0.0966V + 0.000526G + 0.5588V(B) - 0.00304G(B))}$

where

$K = -0.097$ for box configurations

$B = \log_{10}(20.22) = 1.3058$

$V = 0.48kV$

$G = 25$ mm

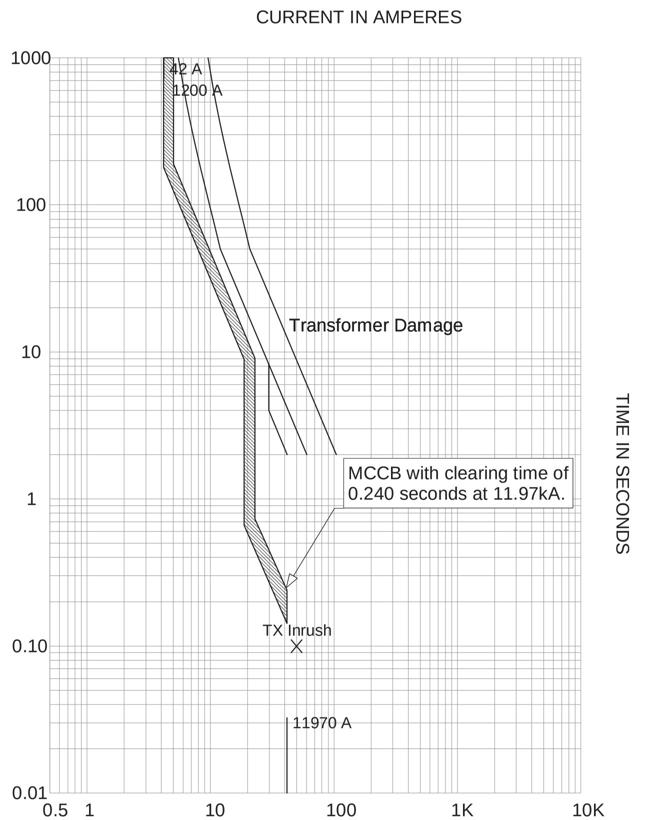
$I_a = 10^{(-0.097 + 0.662(1.3058) + 0.0966(0.48) + 0.000526(25) + 0.5588(0.48)(1.3058) - 0.00304(25)(1.3058))}$

$I_a = 11.97kA$

Now calculate a second arc current at 85% of I_a

85% $I_a = (0.85)11.97kA = 10.17kA$

Step 2 - Determine the Fault Clearing Time from the TCC

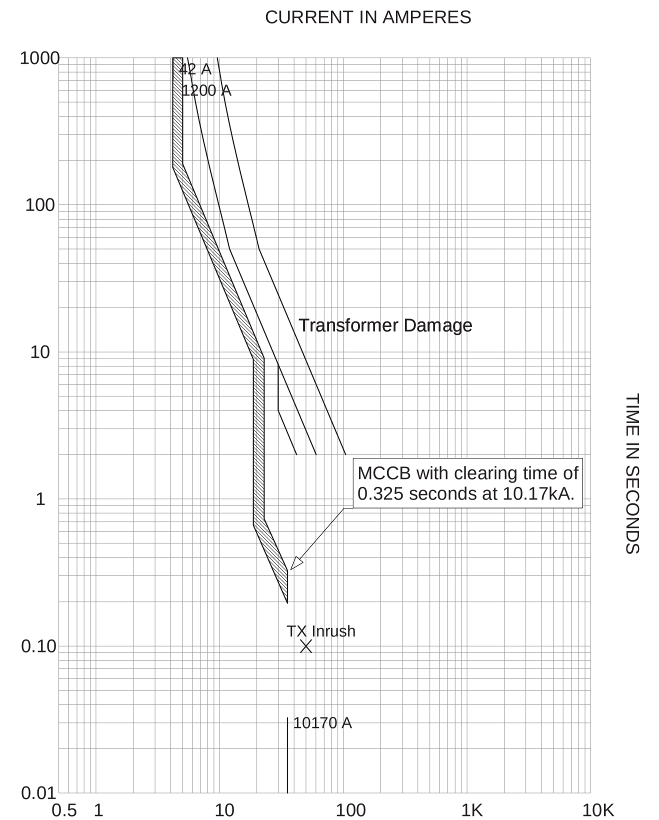


TX.tcc Ref. Voltage: 13800 Current Scale x10^1 One Line Diagram.drw

Fig. 2 TCC for Arc Currents of 11.97kA

The clearing time for the LV MCB at 11.97kA is 0.24 seconds.

Step 2 – cont'd



TX.tcc Ref. Voltage: 13800 Current Scale x10^1 One Line Diagram.drw

Fig. 3 TCC for Arc Currents of 10.17kA

The clearing time for the LV MCB at 10.17kA is 0.325 seconds.

Step 3 – Calculate the Incident Energy using (4)

$E = 4.184C_f(10^{(K1 + K2 + 1.081C + 0.0011G)})(t/0.2)(610/D)^x$

where

$C_f = 1.5$

$K1 = -0.555$

$K2 = -0.113$

$C = \log(11.97) = 1.078$

$G = 25$ mm from Table 1

$t = 0.24$ seconds

$D = 455$ mm from Table 2

$x = 1.641$ from Table 3

$E = 4.184(1.5)(10^{(-0.555 - 0.113 + 1.081(1.078) + 0.0011(25))})(0.24/0.2)(610/455)^{1.641}$

$E = 40.8\ J/cm^2$

$E = (40.8\ J/cm^2)/(4.1868\ J/cal) = 9.7\ cal/cm^2$

Step 3 – cont'd

At 85% I_a

$E = 4.184(1.5)(10^{(-0.555 - 0.113 + 1.081(C) + 0.0011(25))})(0.325/0.2)(610/455)^{1.641}$

where

$C = \log(10.17) = 1.007$

$t = 0.325$ seconds

$E = 46.3\ J/cm^2$

$E = (46.3\ J/cm^2)/(4.1868\ J/cal) = 11.1\ cal/cm^2$

Step 4 - Determine the Clothing Class

$IE = 9.7\ cal/cm^2 < 25.0\ cal/cm^2 \therefore$ class 3 clothing

At 85% I_a

$IE = 11.1\ cal/cm^2 < 25.0\ cal/cm^2 \therefore$ class 3 clothing

Step 5 – Calculate the Arc Flash Boundary

where

$x = 1.641$

$D_B = [4.184(1.5)(10^{(-0.555 - 0.113 + 1.081(1.078) + 0.0011(25)})(0.24/0.2)(610^x/5)]^{1/x}$

$D_B = 1635$ mm

$D_B = (1635\ \cancel{mm})/(1\ in/25.4\ \cancel{mm}) = 64.4$ in

At 85% I_a

$D_B = [4.184(1.5)(10^{(-0.555 - 0.113 + 1.081(1.007) + 0.0011(25)})(0.325/0.2)(610^x/5)]^{1/x}$

$D_B = 1766$ mm

$D_B = (1766\ \cancel{mm})/(1\ in/25.4\ \cancel{mm}) = 69.5$ in

About the Author

Tom Smith holds Bachelors degrees in Electrical Engineering and Education from the University of Nebraska and is a registered Professional Engineer. He began his career at the U.S. Army Corps of Engineers Omaha District in 1983. He joined the Reading offices of Gilbert /Commonwealth in 1988. He has served as a consulting engineer since 1995.

His experience includes the design and analysis of commercial, industrial and utility electrical distribution systems. He also teaches several courses in load flow, motor starting, short circuit, overcurrent coordination and arc flash.

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