

Analysis of Arc Flash in Utility Power Systems

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ABSTRACT: The electric utility business is an inherently dangerous area to work in with employees exposed to many potential hazards daily. One such hazard is an arc flash. An arc flash is a rapid release of energy, referred to as incident energy, caused by an electric arc.

In this project, we are going to take 3 bus systems with the load of 3000 houses. The arc will be created when the bus system change over due to voltage failure, switch disconnect, circuit breaker failure and relay failure. We can't predict the level of the arc before its creating. We are using matlab software to find the created arc level. In that first we will create the generator part, and then will pass the supply to the load with the help of bus system. When, changeover of the bus system, within a short period, the voltage and current value will be simultaneously increase. So we can calculate the voltage and current to get the energy value released. We use empirical equation to find the arc value. To get the difference between current failure and fault failure, we use Linearity of Incident Energy.

This report goes into the depth of the history of arc-flash hazards, analysis methods, both software and empirical derived equations, issues of concern with calculation methods and the work conducted at power transmission system. This work also produced two offline software products to conduct and verify an offline arc-flash hazard analysis

I. INTRODUCTION

Electric utility equipment, like any other product we use in everyday activities, is prone to failure and requires preventative maintenance and repair. During these maintenance activities, employees become exposed to a potential arc-flash incident. An arc-flash incident is a violent event exposing employees to not only high temperatures and noise levels but also shrapnel from the equipment involved in the arc flash. This incident may be caused by the employee themselves or by a random equipment failure on nearby equipment. Effective January 1st, 2009 NESC requires that an arc-flash assessment be performed by companies whose employees work on or near energized equipment to determine the potential exposure to an electric arc employers are. For this reason detailed research has been conducted on the behavior of arc flashes and empirical equations have been developed to predict the energy released during the event and IEEE Std. 1584-2002 enforces the equations. Arc-flash assessments are not easy studies to conduct. These studies require both knowledge of the power system and the protective devices used on the system. The effort required to conduct a full system analysis has been greatly reduced with the integration of arc-flash analysis tools in present short circuit software in coordination with protective device data. The largest effort required in an arc-flash assessment is data collection. There are many variables required as inputs into the detailed equations developed. Some of these variables are also used in short circuit analyses and are readily available while some require engineering judgment to determine which variable to use. The arc energy could be calculated by hand but this also requires a large effort and close attention when entering the data. Several short circuit software programs have implemented an arc-flash analysis module. The objective of the project is to perform arcflash assessment to ensure that the company was in compliance with the NESC standards. And also it discusses the history of arc-flash hazards, pre-existing work to develop the empirical equations used to calculate the incident energy released during the arc flash, and the behavior of arcs. And it explains the different ways to determine the potential incident energy at a location on the system by using the empirical

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equations by using tables developed by the NESC based on system parameters. Also it details the methodology of benchmarking the software package against the empirical equations. It also discusses the level of energy exposure due to protective coordination and the voltage level at the fault location.

II. LITERATURE SEARCH

Recent changes in workplace safety regulations have heightened the awareness of hazards associated with electrical arcs. The hazard level must be quantified and workers properly protected before entering proximity of exposed energized conductors. National Fire Protection Association's (NFPA) standard 70E provides the guidelines for work involving electrical hazards and the selection of arc flash protective equipment. In order to properly select the protective gear one must have knowledge of the potential thermal energy of the electric arc. Institute of Electrical and Electronics Engineers (IEEE) standard 1584 has been the de facto standard for calculating the arc energy levels at different points in the electrical power system. However, NFPA 70E also provides the option of using the Hazard/Risk Category (HRC) task tables for personal protective equipment (PPE) selection. These tables provide pre-defined levels of PPE, which are based on the available short circuit current and the speed of the overcurrent protective device. Therefore, in order to properly apply the tables, some degree of electrical calculations must be performed and the tables could be subjected to misuse if they are applied without knowledge of the necessary calculations. In this paper the basic differences between the IEEE 1584 method and the NFPA 70E task tables are discussed and a recommended specification is provided for facility owners who are interested in achieving compliance with the regulations.

An arc-flash hazard, as defined by IEEE Std. 1584-2002, is a dangerous condition associated with the release of energy caused by an electric arc. The release of energy is caused by an electric current passing through air between ungrounded conductors or between ungrounded conductors and grounded conductors which is capable of producing temperatures of 35,000oF. Exposure to these temperatures can burn human skin and ignite the clothing, adding to the burn injury. These high temperatures also cause the explosive expansion of both the surrounding air and the metal in the arc path.

I chose to do my senior design project on the topic of Arc Flash Analysis. The last few years have developed a great increase in the awareness of arc flash hazards. The analysis is applied to the overall electrical system of utility companies. The purpose of the study is to develop the best way to limit the amount of an arc flash lineman can be exposed to while doing maintenance in the field. The National Electric Safety Code (NESC)-2007 Rule 410 states "employers shall ensure that an assessment is performed to determine the potential exposure to an electric arc for employees who work on or near energized parts or equipment. If the assessment determines a potential employee exposure, greater than 2 cal/cm² exists, the employer shall require employees to wear clothing or clothing systems that have an effective arc rating not less than the anticipated level of arc energy." Electricity has proposed a serious hazard since its discovery by Benjamin Franklin. Why though, after over a hundred years, is the awareness of this hazard drawing so much attention? Arc flash analysis can propose a serious problem to utility companies. Most injuries that occur out in the field with lineman who work for power utility companies don't result from electrocution, but rather from an arc flash. Over the years, these companies install protective devices all throughout a system. However, much effort, time and cost is involved to ensure these protective devices coordinate with other devices and are used to their best efficiency. These protective devices cannot be changed instantaneously to help arc flashes. One job of a consulting engineer is to calculate the arc flash incident energy at the point of contact. It then can be determined if the up line protective device is adequate, or if a recommendation to their protective devices needs to be applied. When the first arc flash assessment was created there were a few key design questions that needed to be thought about: 1. What are the requirements? 2. How long do we have to design? 3. How will it be tested? 4. What recommended improvements can be made to client? This study has shown that a procedure can be implemented for utility companies. Steps and procedures were developed to perform an accurate arc flash analysis. However, is this the best method that can be used? How accurate are these calculations? Although it has been learned that there isn't a 100% right solution, an accurate and reliable analysis can be created. Future work for this study will be to come up with the most accurate and reliable method.

Copper, a metal commonly used in electric equipment, expands by a factor of 67,000 times when it turns from a solid to a vapor. The expansion of the air and metal can cause high pressures, intense sound, and flying shrapnel. The high

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pressures can exceed hundreds or even thousands of pounds per square foot, possibly knocking workers off ladders, rupturing eardrums, and collapsing lungs. The sounds associated with these pressures can exceed 160 dB resulting in hearing damage. The shrapnel and molten metal will be expelled away from the arc at speeds exceeding 700 miles per hour which is fast enough to completely penetrate the human body. Each year at least 2,000 people in the U.S. are admitted to burn centers with severe arc-flash burns. Arc flashes can and do kill at distances of 10 feet [2].

According to the NESC 2007 edition Part 4, effective January 1, 2009 employers shall ensure that an assessment is performed to determine potential exposure to an electric arc for employees who work on or near energized parts or equipment. The assessment is to determine the potential incident energy levels to which employees could be exposed while performing work on energized equipment.⁵ If the assessment reveals that the potential exposure is greater than 2 cal/cm² at the distance the employee is working from the energized parts (1.2 cal/cm² is equivalent to the onset of a second degree burn) the employer shall require the employee to wear

clothing or a clothing system that has an effective arc rating not less than the anticipated level of arc energy. When an arc-flash hazard analysis is performed, it shall include a calculation of the estimated arc energy based on the available fault current, the duration of the arc (cycles), and the distance from the arc to the employee. Two exceptions to the analysis are listed below [3]. The clothing or clothing system level required to be worn based on the potential energy released will be discussed in the Chapter 3. EXCEPTION 1: If the clothing required by this rule has the potential to create additional and greater hazards than the possible exposure to the heat energy of the electric arc, then clothing with an arc rating or arc thermal performance value (ATPV) less than that required by the rule can be worn. EXCEPTION 2: For secondary systems below 1000 V, applicable work rules required by this part and engineering controls shall be utilized to limit exposure. In lieu of performing an arc-flash hazard analysis, clothing or a clothing system with a minimum effective arc rating of 4 cal/cm² shall be required to limit the likelihood of ignition.

Arc-Flash Calculation Methods

A few years ago, the term “arc flash” crept into our electrical technical vocabulary. Since that time, performing arc flash calculations remains a challenge for many of us. Calculating incident energy levels and arc flash boundary distances for the purpose of estimating the hazard risk category (HRC) a worker would be exposed to while working on electrical equipment opens a window into the inner workings of the power distribution system. Arc flash calculations can tell us a great deal about how the system will behave during a fault condition. They also offer us a golden opportunity to optimize the system for safety and attempt to prevent the hazard from happening in the first place.

Arc flash regulations may be one of the best things that have ever happened to electrical designs, because they force engineers to look closer at details they might have otherwise overlooked in the past and put the power system calculations front and center in the design process. The very notion of considering arc flash early on in the design of a power distribution system is not only prudent, but also economical.

3.1 Applicable Standards

There are a couple different methods proposed to conduct an arc-flash analysis.

The two methods addressed and examined with this project are IEEE Std. 1584-2002, *Guide for Performing Arc-Flash Hazard Calculations* and NESC C2-2007. Each of these will be discussed in detail in this chapter. When using the IEEE equations to determine the incident energy of a specific point in a system, such as at a bus or switchgear, the equations look and seem overwhelming because of the many variables used which also vary based on the voltage of the system. Along with the many variables there are a few steps that need to be followed in order to calculate the incident energy. These steps are shown below along with the equations needed in each. It should be noted that these equations are not valid for single phase or dc systems. These models are based on measured arc current incident energy under a specific set of test conditions and on theoretical work. These models will enable users to calculate the estimated maximum incident energy and the estimated arc-flash boundary distance. Real arc exposures may be more or less severe than indicated by these models. The first step that needs to be conducted is to determine the bolted fault current at the point in the system that is being analyzed. The three phase fault current at the location is needed for these calculations. The next step is to determine the voltage level at the point of interest. Voltage levels are broken up into two different categories, less than 1 kV and 1 to 15 kV, and based on these ranges different equations are used to

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calculate the arcing current. For voltages less than 1 kV (3.1) is used and for voltages from 1 kV to 15 kV (3.2) is used. Both equations are shown below along with what each of the variables represent. The equation for voltages greater than 15 kV will be discussed later.

3.2 Empirical Equations

For applications with a system voltage less than or equal to 1 kV,

$$l_g I_a = K + 0.662 * l_g I_F + 0.0966 * V + 0.000526 * G + 0.558 * V * (l_g I_F) - 0.00304 * G * (l_g I_F) \quad (3.1)$$

For applications with a system voltage of 1 to 15 kV,

$$l_g I_a = 0.00402 + 0.983 * l_g I_F \quad (3.2)$$

where

$l_g = \log_{10}$

$I_a =$ arcing current (kA)

$K = -0.153$ for open configurations (no enclosure) and -0.097 for box configurations (enclosed equipment)

$I_F =$ bolted fault current for three-phase faults (symmetrical RMS) (kA)

$V =$ system voltages (kV)

$G =$ gap between conductors (mm)

Table 3-1 provides a list of equipment for the different voltage classes, the typical gap between conductors of that equipment and a distance factor that will be used in later equations.

By raising 10 to the power of $l_g I_a$ in (3.3),

$$I_a = 10^{l_g I_a} \quad (3.3)$$

arcing current is determined and can be used in following equations for the incident energy. The next step in the analysis is to calculate the incident energy based on data normalized for an arc of 0.2 seconds and distance from the possible arc point to the person of 610 mm. (3.4) is used in the calculation for both voltage ranges of less than or equal to 1 kV and 1 to 15 kV

$$l_g E_n = K_1 + K_2 + 1.081 * l_g I_a + 0.0011 * G \quad (3.4)$$

where

$E_n =$ incident energy (J/cm²) normalized for time and distance

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K1 = -0.792 for open configurations (no enclosure) and -0.555 for box configurations (enclosed equipment)
K2 = 0 for ungrounded and high-resistance grounded systems and -0.113 for grounded systems
G = gap between conductors (mm) (Table 3.1)

By raising 10 to the power of lgEn in (3.5), incident energy can be used in (3.6) to convert from the normalized state.

$$E_a = 10^{lgE_n} \tag{3.5}$$

After calculating the normalized incident energy, it must be converted to cal/cm² at the specific working distance and with the devices clearing time. (3.6) is used in the conversion

$$E = 4.184 * C_f * E_a * \left(\frac{t}{0.2}\right) * \left(\frac{610^X}{D^X}\right) * 0.24 \tag{3.6}$$

where

E = incident energy (cal/cm²)
Cf = calculation factor
Ea = normalized incident energy
t = arcing time (seconds)
D = working distance (mm)
X = distance exponent (Table 3.1)
0.24 = conversion factor

These equations are valid for voltages up to 15 kV and arc gaps between 10 and 153 mm. Equations associated with equipment up to 15 kV are based on the lab testing and data used to develop (2.1) and (2.2) and are applied in the IEEE Std. 1584- 2002. When the voltages are greater than 15 kV or the arc gap is outside of the range, a theoretical equation, called the Lee Equation, is used as shown in (3.7) where the arccurrent is considered to be equal to the bolted fault current. This equation is also applied in the IEEE Std. 1584-2002.

$$E = 2.142 * 10^6 * V * I_a * \left(\frac{t}{D^2}\right) * 0.24 \tag{3.7}$$

where

E = incident energy (cal/cm²)
V = system voltage (kV)
t = arcing time (seconds)
D = working distance (mm)
Ia = bolted fault current (kA)

The next step in the calculations is to determine the flash protection boundary. This is an approach distance at which a worker will receive a second-degree burn if an arc flash would occur; this is the level of 1.2 cal/cm². (3.8) provides the equation to determine this distance

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$$D_b = \left[4.184 * C_f * E_a * \left(\frac{t}{0.2} \right) * \left(\frac{610^X}{E_b} \right) \right]^{\frac{1}{X}} \quad (3.8)$$

where

Db = distance of flash protection boundary from arc (mm)

Cf = calculation factor of 1.5 for voltages less than or equal to 1 kV

Ea = normalized incident energy

Eb = incident energy in J/cm² at the flash protection boundary: typically 5 J/cm² which is equal to 1.2 cal/cm²

t = arcing time (seconds)

X = distance exponent

610 = normalized distance of 24 inches converted to millimeters

0.2 = normalized 0.2 second clearing time

(3.8) is based on the current being interrupted by a non-current limiting device.

Additional equations are needed if these devices are present.

Table 3.2: PPE required given equipment voltage, fault current and clearing time

Phase-to-phase voltage (kV)	Fault current (kA)	4-cal System	8-cal System	12-cal System
		Maximum clearing times in cycles (seconds)	Maximum clearing times in cycles (seconds)	Maximum clearing times in cycles (seconds)
1 to 15	5	46.5	93	139.5
	10	18	36.1	54.1
	15	10	20.1	30.1
	20	6.5	13	19.5
15.1 to 25	5	27.6	55.2	82.8
	10	11.4	22.7	34.1
	15	6.6	13.2	19.8
	20	4.4	8.8	13.2
25.1 to 36	5	20.9	41.7	62.6
	10	8.8	17.6	26.5
	15	5.2	10.4	15.7
	20	3.5	7.1	10.6
36.1 to 46	5	16.2	32.4	48.6
	10	7	13.9	20.9
	15	4.3	8.5	12.8
	20	3	6.1	9.1

This table was built using a commercially available computer software program, not specifically listed in the NESC documentation. Also this table is based on an open air phase-to-ground arc and is not intended to be used for phase-to-phase arcs or enclosed arcs. Assumptions of a 15 inch separation from the arc to the employee and arc gaps of 2 inches for 1 to 15 kV, 4 inches for 15.1 to 25 kV, 6 inches for 25.1 to 36 kV and 9 inches for 36.1 to 46 kV based on the IEEE

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Standard 4-1995 [3]. Table 3.3 provides the same information except for voltages from 46.1 to 800 kV was also developed using a computer software program and has its own list of assumptions. First, the air gap was calculated by using the phase-to-ground voltage and dividing by 10; this represents the dielectric strength of air at 10 kV per inch. Second, the distance from the arc was calculated by using the minimum approach distance from Table 441-2 in the NESC-2007 and subtracting two times the assumed arc gap length.

Table 3.3: Live-line tool work PPE required given equipment voltage, fault current and clearing time

Phase-to-phase voltage (kV)	Fault current (kA)	4-cal System	8-cal System	12-cal System
		Maximum clearing times in cycles (seconds)	Maximum clearing times in cycles (seconds)	Maximum clearing times in cycles (seconds)
46.1 to 72.5	20	8.5	17	25.5
	30	5.3	10.5	15.8
	40	3.7	7.3	11
	50	2.8	5.5	8.3
72.6 to 121	20	8.2	16.5	24.7
	30	4.7	9.4	14.1
	40	3.1	6.2	9.3
	50	2.2	4.4	6.6
138 to 145	20	9.8	19.5	29.3
	30	5.6	11.2	16.8
	40	3.7	7.4	11.1
	50	2.6	5.3	7.9
161 to 169	20	9.3	18.6	27.9
	30	5.7	11.5	17.2
	40	4	8	12
	50	3	6	9
230 to 242	20	10.4	20.9	31.3
	30	6.4	12.9	19.3
	40	4.5	9	13.5
	50	3.4	6.8	10.1
345 to 362	20	22.6	45.3	67.9
	30	14	28.1	42.1
	40	9.8	19.6	29.4
	50	7.4	14.7	22.1
500 to 550	20	18.9	37.8	56.7
	30	11.7	23.3	35
	40	8.1	16.3	24.4
	50	6.1	12.2	18.3
765 to 800	20	43.6	87.3	130.9
	30	27	53.9	80.9
	40	18.9	37.8	56.7
	50	14.2	28.4	42.6

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IV. MATLAB SOFTWARE

Language Features for Matlab

Matlab language has the following characteristics:

(1) Programming efficiency

It is a scientific and engineering calculation for high-level language that allows the form of mathematical programming language. Fortran and C and other languages written in the formula closer to our way of thinking, like using Matlab programming paper in calculus arrange on a formula and solve problems. Therefore, Matlab language, popularly known as the calculus can also be paper-based science algorithm language because it is easier to write. So the programming and high efficiency, everyone can easy to learn.

(2) Easy to use

Matlab language is an interpreted language (in no special tools are compiled before), it is flexible. That means of its rich debugger, debugging speed, less time to learn. Matlab language compare with other languages, has solved these problems, edit, compile, link and execute integration. It can be flexible in the same operation on the screen quickly ruled out entering the program in writing. And Matlab also have grammatical errors as well as semantic errors, thereby speeding up the user to write, modify and debug programs faster. If people used Matlab, people will know Matlab' advantage.

(3) Expansion capability

High version of the Matlab language has rich library functions, when carrying out complex mathematical operations can be called directly. And the Matlab library functions in the form on file with the same user, so users can file as a library of Matlab functions to call. Thus, the user can easily build own needs and the expansion of the new library functions. Using of Matlab in order to improve efficiency and expand its capabilities.

(4) Statement is simple, rich in content

The most important ingredient of Matlab language is the most basic function of a varying number of input variables and different number of output variables, representing different meaning (a bit like object-oriented polymorphism). This is not only makes the Matlab library function more feature-rich, while greatly reducing the need for disk space. Making the Matlab of M-file written in a simple, short and efficient.

(5) Efficient and convenient matrix and array operations

Matlab language provides for matrix arithmetic operators, relational operators, logical operators, conditional operators and assignment operator. But most of these operators can be copied without any change in operations between the array, such as arithmetic operators increase the "." can be used for operations between arrays. It need not define the dimension of the array, and gives the matrix function. It is much simple, efficient and convenient.

(6) Convenient graphics

Matlab graphics is very convenient. It has a range of drawing functions. In addition, call the drawing function to adjust the color argument can be drawn the same point, line, double line or multiple lines. The design for the sake of this research is a common programming language that fall.

In short, Matlab language design can be said to represent the current high-level computer language development.

V. TESTING

Introduction:

Is the menu bar displayed in the appropriate contested some system related features included either in menus or tools? Do pull –Down menu operation and Tool-bars work properly? Are all menu function and pull down sub function properly listed ?; Is it possible to invoke each menu function using a logical assumptions that if all parts of the system are correct, the goal will be successfully achieved .? In adequate testing or non-testing will leads to errors that may appear few months later.

This create two problem

1. Time delay between the cause and appearance of the problem.
2. The effect of the system errors on files and records within the system

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The purpose of the system testing is to consider all the likely variations to which it will be suggested and push the systems to limits.

The testing process focuses on the logical intervals of the software ensuring that all statements have been tested and on functional interval is conducting tests to uncover errors and ensure that defined input will produce actual results that agree with the required results. Program level testing, modules level testing integrated and carried out.

Testing Methods

There are two major type of testing they are

- 1) White Box Testing.
- 2) Black Box Testing.

5.1 WHITE BOX TESTING:

White box sometimes called “Glass box testing” is a test case design uses the control structure of the procedural design to drive test case.

Using white box testing methods, the following tests were made on the system

- a) All independent paths within a module have been exercised once. In our system, ensuring that case was selected and executed checked all case structures. The bugs that were prevailing in some part of the code where fixed
- b) All logical decisions were checked for the truth and falsity of the values.

5.2 BLACK BOX TESTING:

Black box testing focuses on the functional requirements of the software. This is black box testing enables the software engineering to derive a set of input conditions that will fully exercise all functional requirements for a program. Black box testing is not an alternative to white box testing rather it is complementary approach that is likely to uncover a different class of errors that white box methods like..

- 1) Interface errors
- 2) Performance in data structure
- 3) Performance errors
- 4) Initializing and termination errors

5.3 UNIT TESTING:

Unit testing is a software verification and validation method in which a programmer tests if individual units of source code are fit for use. A unit is the smallest testable part of an application. In procedural programming a unit may be an individual function or procedure. Ideally, each test case is independent from the others: substitutes like method stubs, objects, fakes and test harnesses can be used to assist testing a module in isolation.

5.4 INTEGRATION TESTING:

This testing is sometimes called Integration and Testing. Integration testing is the phase in software testing in which individual software modules are combined and tested as a group. It occurs after unit testing and before system testing. Integration testing takes as its input modules that have been unit tested, groups them in larger aggregates, applies tests defined in an integration test plan to those aggregates and delivers as its output the integrated system ready for system testing.

5.5 VALIDATION TESTING:

Validation Testing can be defined in many ways, but a simple definition is that validation succeeds when the software functions in a manner that can reasonably expected by a customer. After validation test has been conducted, one of the following two possible conditions exists. The functions or performance characteristics confirm to specification and are accepted.

- In the administrator and marks modules, all the fields must be filled.
- In the student registration, mobile number should contain exactly 10 numbers.

5.6 USER ACCEPTANCE TESTING:

User acceptance of a system is a key factor of any system. The system under consideration is tested for the acceptance by constantly keeping in touch with the prospective system users at the same time of developing and marketing changes whenever required. This is done in regard to the following points:

- Input Screen Design

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- Output Screen Design

SYSTEM STUDY

FEASIBILITY STUDY

The feasibility of the project is analyzed in this phase and business proposal is put forth with a very general plan for the project and some cost estimates. During system analysis the feasibility study of the proposed system is to be carried out. This is to ensure that the proposed system is not a burden to the company. For feasibility analysis, some understanding of the major requirements for the system is essential.

Three key considerations involved in the feasibility analysis are

- ◆ ECONOMICAL FEASIBILITY
- ◆ TECHNICAL FEASIBILITY
- ◆ SOCIAL FEASIBILITY

ECONOMICAL FEASIBILITY

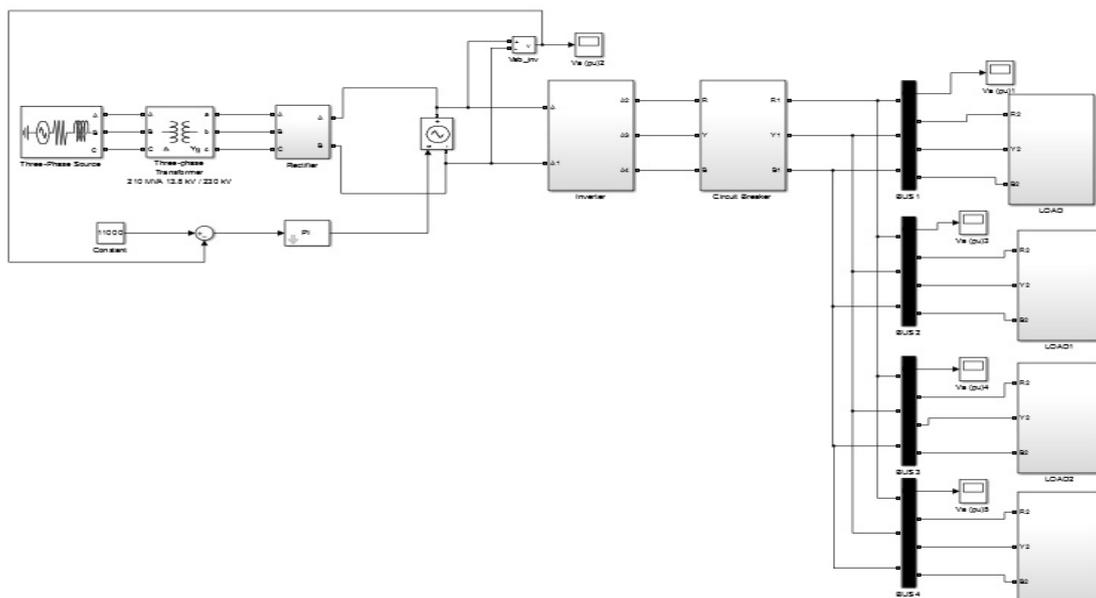
This study is carried out to check the economic impact that the system will have on the organization. The amount of fund that the company can pour into the research and development of the system is limited. The expenditures must be justified. Thus the developed system as well within the budget and this was achieved because most of the technologies used are freely available. Only the customized products had to be purchased.

TECHNICAL FEASIBILITY

This study is carried out to check the technical feasibility, that is, the technical requirements of the system. Any system developed must not have a high demand on the available technical resources. This will lead to high demands on the available technical resources. This will lead to high demands being placed on the client. The developed system must have a modest requirement, as only minimal or null changes are required for implementing this system.

SOCIAL FEASIBILITY

The aspect of study is to check the level of acceptance of the system by the user. This includes the process of training the user to use the system efficiently. The user must not feel threatened by the system, instead must accept it as a necessity. The level of acceptance by the users solely depends on the methods that are employed to educate the user about the system and to make him familiar with it. His level of confidence must be raised so that he is also able to make some constructive criticism, which is welcomed, as he is the final user of the system.



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Three phase source

The Voltage Source block models an ideal three-phase voltage source or a three-phase voltage source with harmonics. You specify the configuration using the Source representation parameter. When you specify the ideal three-phase voltage source representation, the Voltage Source block models an ideal three-phase voltage source that maintains sinusoidal voltage of the specified magnitude across its terminals, independent of the current flowing through the source. When you specify the three-phase voltage source with harmonics representation, the Voltage Source block models a three-phase voltage source that maintains the fundamental frequency and harmonics of the specified magnitude across its terminals, independent of the current flowing through the source. The source has a wye configuration, and port n provides a connection to the center of the wye. Port ~ is an expandable three-phase port representing the three phases, a, b, and c. The current is positive if it flows from positive to the center of the wye, and the voltage across each phase is equal to the difference between the voltage at the positive terminal and the center of the wye, $V(+)-V_n$.

Transformer

The transformer is rated 50W, 60 Hz, 120V/12V and assumed to have an efficiency of 94%, no-load magnetizing current of 1% and a leakage reactance of 2.3%. Core losses are not modeled and the core material B-H characteristic is assumed to be linear. The transformer initially operates under no-load conditions. At time $t=0.5s$, the rated load is turned on. Because of the winding resistances and leakage inductances, the secondary voltage drops from 12 Vrms to 11.3 Vrms and the transformer supplies a full load current of 3.9 Arms on its secondary. The flux and mmf scopes show the operating conditions during no-load and full-load. Compare the leakage flux with the core flux, and observe the primary and secondary-side mmfs.

Rectifier

It converts 120 volts AC to 12 volts DC. The transformer has a turns ratio of 14, stepping the supply down to 8.6 volts rms, i.e. $8.6 \cdot \sqrt{2} = 12$ volts pk-pk. The full-wave bridge rectifier plus capacitor combination then converts this to DC. The resistor represents a typical load. The model can be used to size the capacitor required for a specified load. For a given size of capacitor, as the load resistance is increased, the ripple in the DC voltage increases. The model can also be used to drive an application circuit in order to assess the effect of the ripple. Plot "Bridge Rectifier Voltages and Currents" shows how AC voltage is converted to DC Voltage. The dark blue line is the AC voltage on the source side of the bridge. There are two paths for current flow through the diode bridge. The alternating peaks through diodes 1&4 and diodes 2&3 show that current flow reaching the capacitor is flowing in the same direction even though the polarity of the voltage is changing. The ripple in the load voltage corresponds to the charging and discharging of the capacitor.

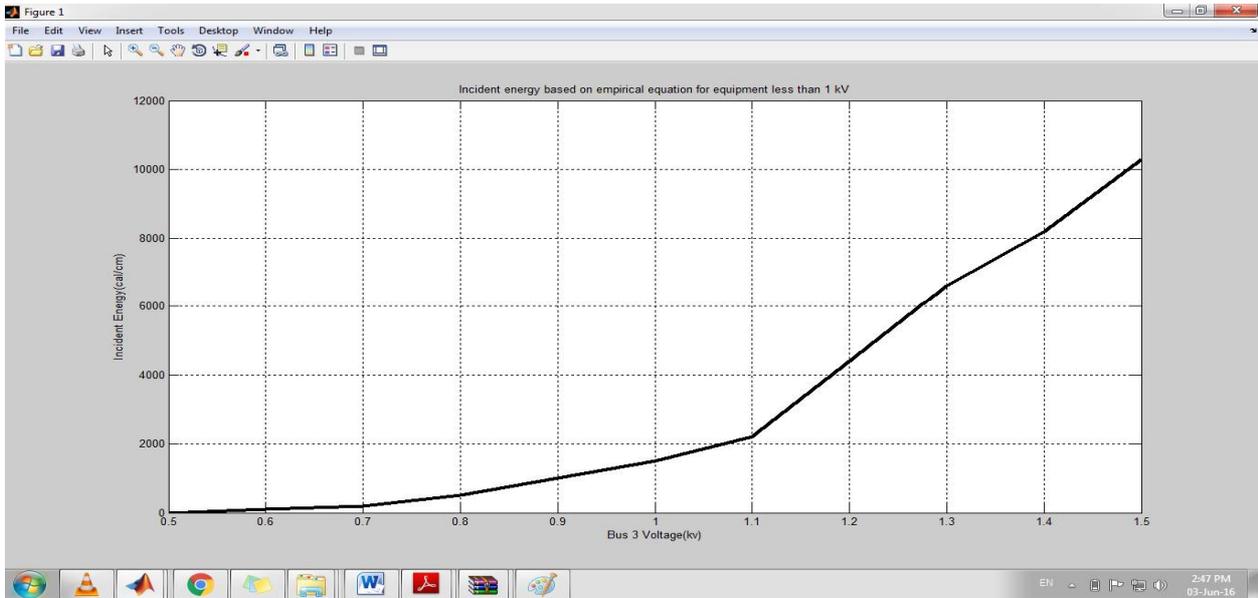
Discontinuity Due to Voltage Levels

The second variable to be evaluated is the voltage level of the equipment. As mentioned earlier in section 3.2, 1 kV is a break point for which equation to use in calculating the arcing current and 15 kV is a break point at which empirical equations are not to be used in analysis but instead the Lee equation. On a typical transmission or distribution system, voltages can range from 0.95 to 1.05 per unit on an intact system. For a 1 kV system the voltage could run between 0.95 to 1.05 kV and for a 15 kV system the voltage range could run between 14.25 and 15.75 kV. This results in two different set of equations to be considered when evaluating one piece of equipment. If the incorrect equation is used, lower levels of incident energy may be calculated in turn causing lower levels of PPE worn by the employee which may not properly protect the individual for an arc-flash incident.

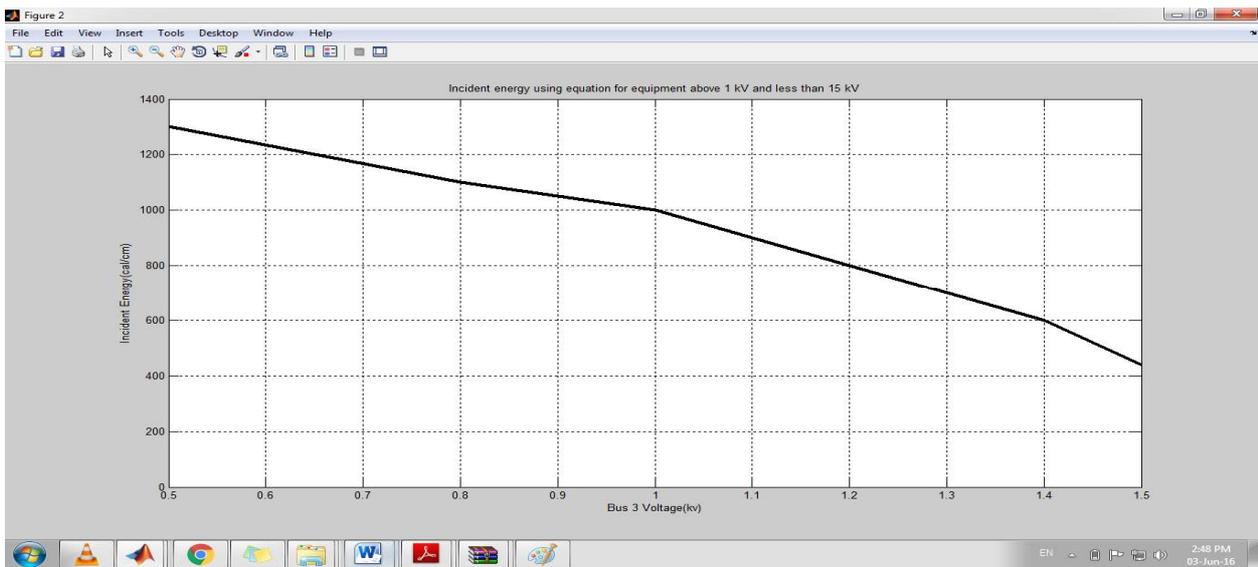
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An evaluation of this condition was studied on the same test system used for the 50/51 contact evaluation. One system was set to a system voltage of 14.9 kV and the second system was set to a voltage level of 15.1 kV displayed in Figure 4.2. The same condition was applied to a 1 kV system except the low level was set to 0.9 kV and the high to 1.1 kV.

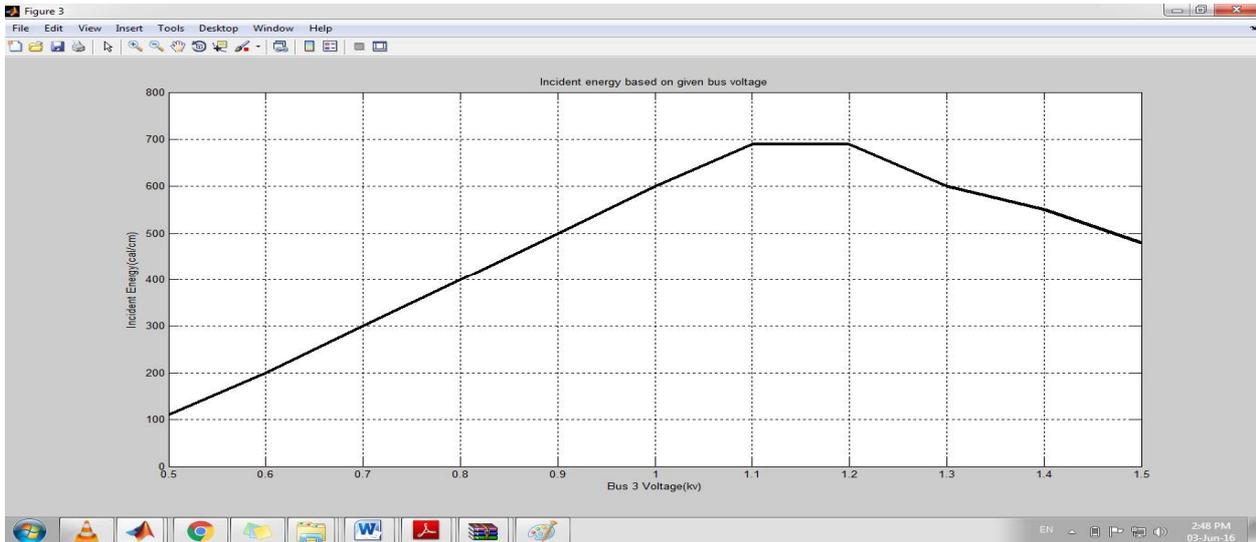


This allows both sets of arc-flash equations to be tested with only a 200 volt difference between the two systems. In the field this could easily be found by placing a distribution capacitor into service to boost service voltages or if the employee is working on the piece of equipment under a lighter load timeframe. As shown in the simulations on the 1 kV system and only using the equation for equipment below 1kV, the incident energy at bus 3 increases exponentially as the voltage increase

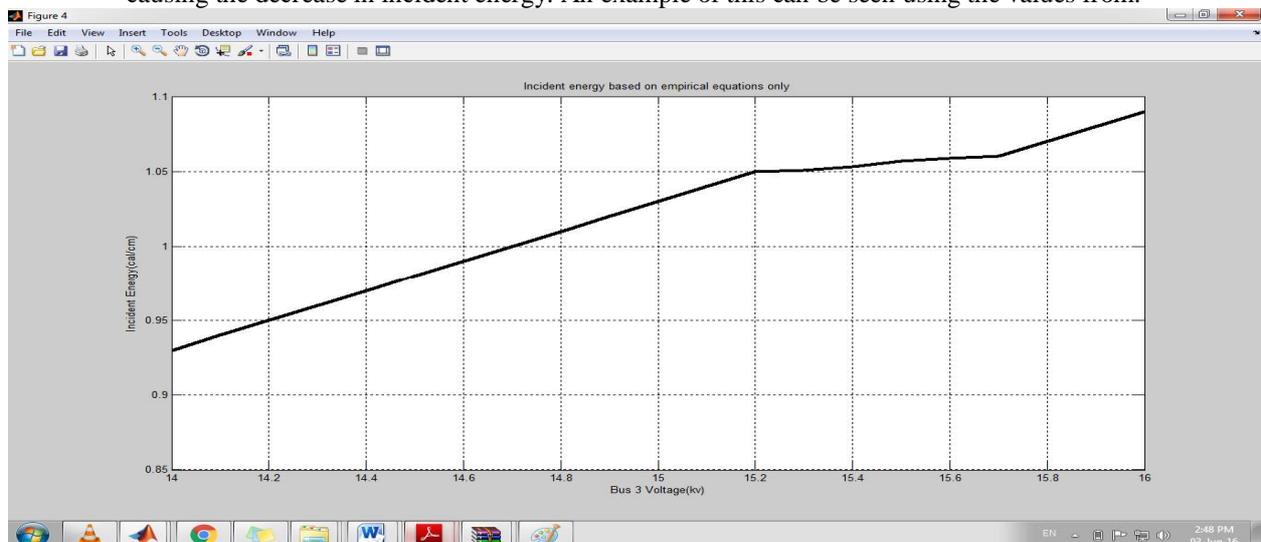
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The opposite trend is found when only using the equation for equipment above 1 kV and less than 15 kV. As it shows, the incident energy increases as the voltage increases until it reaches 1 kV. At this point, the equation for equipment above 1 kV and less than 15 kV takes over and we see a slight increase in incident energy up to 1.1 kV and then the incident energy decreases. The discontinuity can be associated to two factors. First, in the equation for equipment less than 1 kV, (3.1) above, uses the conductor gap to calculate the arcing current. This full value isn't applied to the equation but a fraction of it is, increasing the log of the arcing current available. This gap isn't applied in the equation for equipment greater than 1 kV and less than 15 kV, (3.2) above. Second, in equation (3.1), the equipment voltage is used to calculate the arcing current. When the voltage is less than 1 kV, this applies a fraction of the log of the arcing current. When the log of the arcing current is then applied to find the normalized incident energy, the normalized incident energy is also reduced. Once the voltage is greater than 1 kV, the log of the arcing currents starts to decrease causing the decrease in incident energy. An example of this can be seen using the values from.



the test system. When the voltage is at 900 volts, the I_{gIa} is equal to 3.55 kA when using equation (3.1) and 3.76 kA when using equation (3.2). When the voltage is at 1.1 kV, the I_{gIa} is equal to 3.92 kA when using equation (3.1) and 3.68 kA when using equation (3.2). If the voltage was to be applied in the equation (3.1), there would be a multiplying

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factor anywhere from 1.1 to 15 times and the incident energy would continue to increase. As shown in the simulation, the incident energy of both buses in the 15.1 kV system increased to levels well above the level found in the 14.9 kV system. For bus 2 the incident energy increased from 5.5 to 130.16 cal/cm² and bus 3 increased from 1.0 to 25.01 cal/cm². Figure 4.6 is a plot of the bus 3 incident energy against the bus 3 voltage using the derived equations only based off of lab testing. We see that as the voltage increases the incident energy increases linearly. As it shows, at the 15 kV voltage level, the incident energy makes a significant jump from around 1 cal/cm² up to above 24 cal/cm². This is due to the change to using the Lee Equation. It should be noted that the significant change does not occur in a real life application. The equipment under analysis would provide similar incident energy levels whether the voltage was at 14.9 or 15.1 kV. Using the higher incident energy could cause employees to wear over bearing PPE potentially causing more risk during their job duties and require wrong field labels placed on the equipment. Also, if the incident energy levels were high enough that the equipment would need to be de-energized before the employee could perform their job, this could cause jeopardy to the reliability of the system and lost revenue to the company. If lab tests were to be conducted on equipment with voltages greater than 15 kV, the derived equations potentially would continue linearly and not provide the significant jump causing unrealistic incident energy levels. Equipment around the 15 kV level should be examined closely by hand to verify the correct incident energy is being applied to the system.

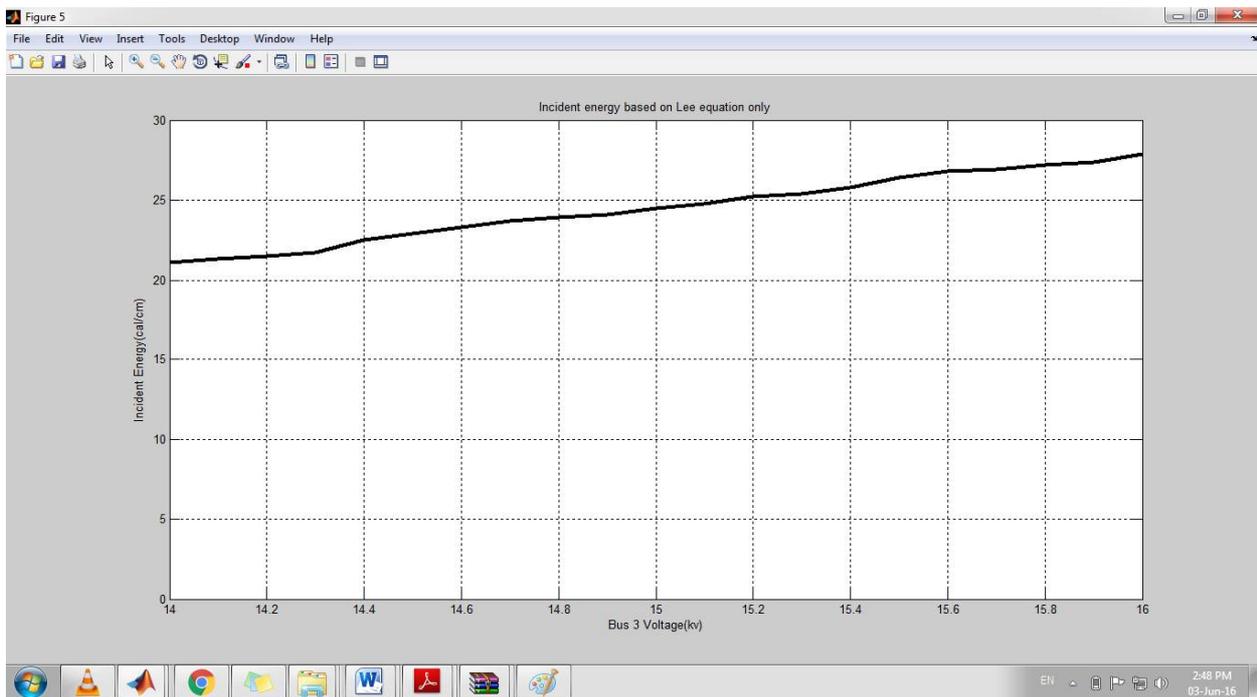
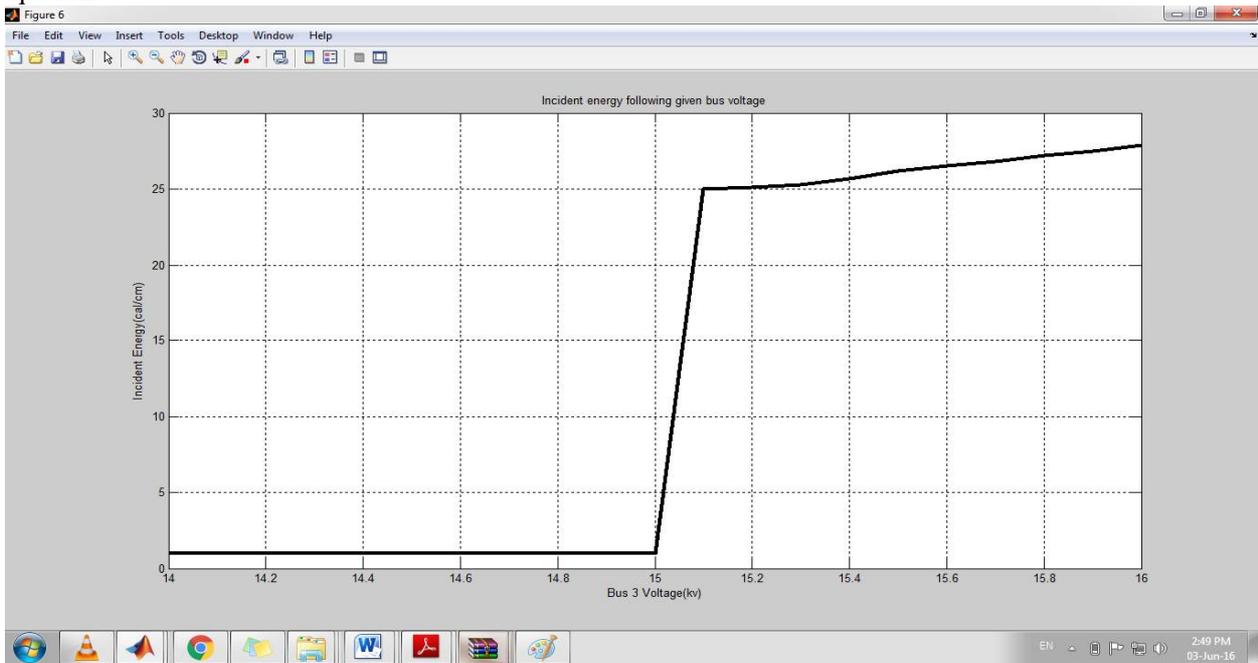
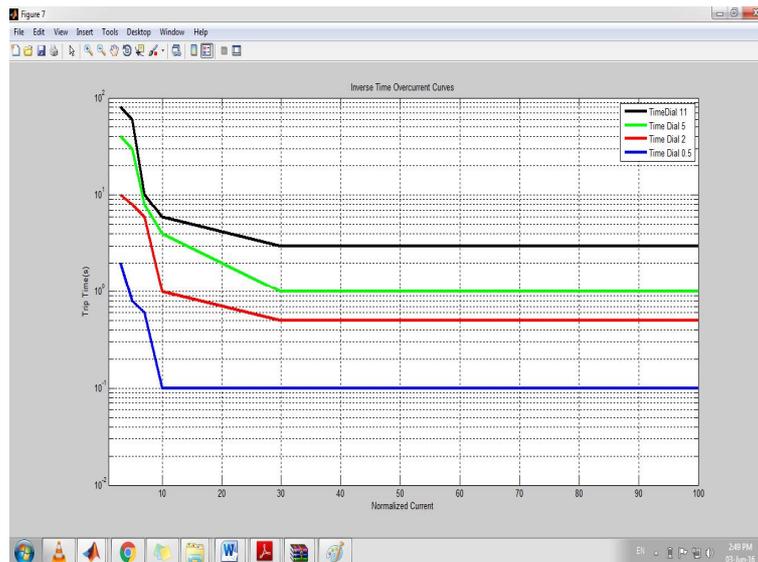


Table 4.1 has the incident energy calculated from the voltage test system based on which set of equations were selected. These values were used to create Table 4.2 has the incident energy calculated from the voltage test system based on which set of equations were selected. This is especially concerning due to the fact the NESC does not specify at what conditions the analysis is to be conducted; i.e. under light load or peak load conditions. 33 Special consideration needs to be taken when analyzing systems where the voltage of the equipment can vary between two different sets of

equations



When comparing the incident energy levels over a range of possible current levels, both load and fault levels, it needs to be mentioned that the incident energy increase linearly and not exponentially. Figure 4.9 shows a standard U.S. U2 inverse time overcurrent curve of tripping times of a relay, either in a mechanical or electrical relay.



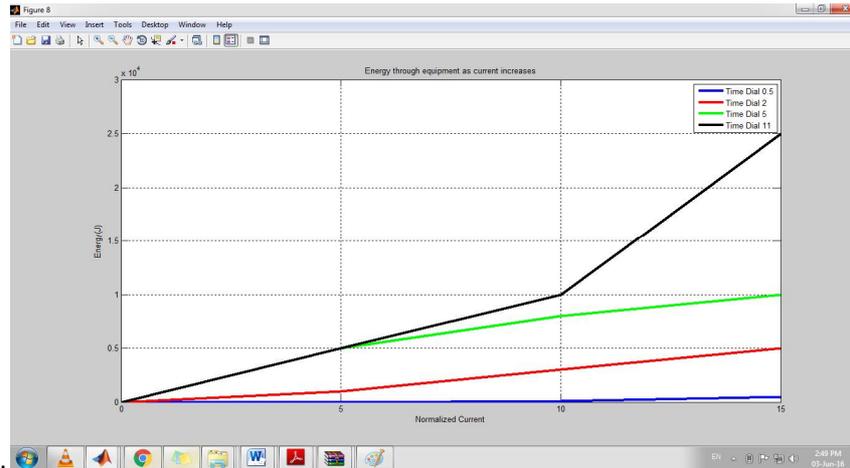
When the overcurrent curves are applied to a piece of equipment and the energy through the equipment is calculated, it can be seen that the energy increases exponentially. Figure 4.10 depicts energy through a 6 inch piece of copper over a range of currents. In the equation for energy, the resistance is held constant; independent of the current. As the current increases the total time the current is applied to the equipment decreases due to the inverse overcurrent curve. Since the

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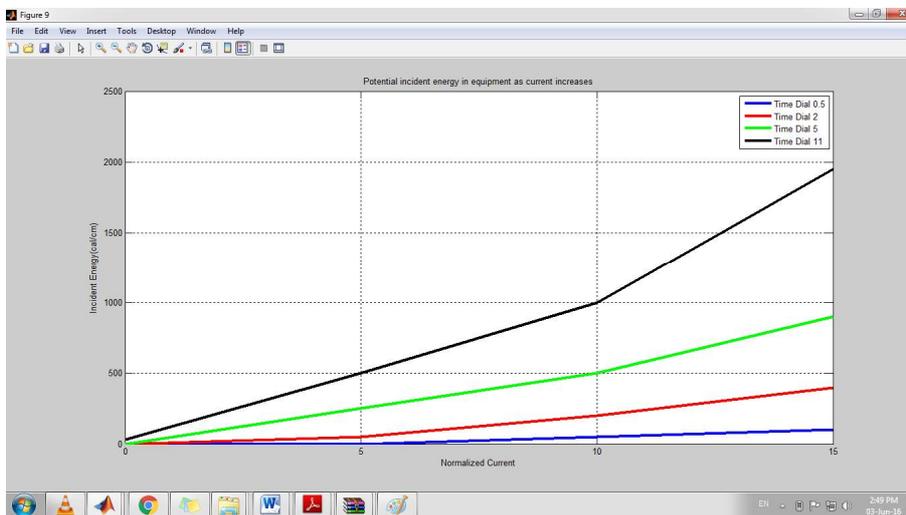
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current is squared and the value of the current is much larger than any component in the equation, the energy curve becomes exponential



Now looking at the plots of the incident energy in Figure 4.11, using the same overcurrent curves and range of currents, the incident energy is linear. This is due to the fact that never in the equation is the current squared.



It needs to be noted that the energy calculated is only in Joules and is not directly comparable to cal/cm², which is what incident energy is measured in. These plots are shown to depict the discontinuity of the calculated level of energy between the two sets of equations. All data for the three plots in section 4.3 can be found in Appendix F. The parameters and assumptions used to build Figures 4.10 and 4.11 are as follows, the relay was using a 600/5 current transformer, tap setting of 6 amps, normal load current of 700 amps, a piece of wire 6 inches long with a diameter of 0.005 meters resulting in a resistance of 0.0001314 ohms and a system voltage between 1 kV and less than 15 kV.

VI. CONCLUSION

Discontinuity around equipment at 15 kV can be associated to two variables. The first is the system voltage is a variable in the Lee Equation and not in the empirical equation. This adds a multiple of at least 15.1 to the incident

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energy equation. The second is the full fault current is applied to the Lee Equation and the arcing current, which is a fraction of the fault current, is applied to the empirical equation.

The arc-flash analysis tool were developed to perform an analysis by hand without causing the user to enter values into multiple equations with the risk of entering the incorrect constants.

The incident energy increases linearly in both the derived equations and in the Lee equation as the voltage is changed. When the voltage changes from 15 to 15.1 kV, the calculated incident energy can increase by 25 times the level with the Lee equation.

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