IMPACT OF AVAILABLE FAULT CURRENT VARIATIONS ON ARC-FLASH CALCULATIONS

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***Abstract* – Prior to the arrival of the arc-flash hazard analysis and incident energy calculations, it was common practice to perform short-circuit studies assuming an infinite source on the primary of the service transformer. With the main goal of a short-circuit study being to compare the maximum calculated short-circuit current to the short-circuit rating of protective devices, using an infinite source resulted in the most conservative short-circuit current. However, since the amount of energy available in an arc-flash incident is not only dependent on the available short-circuit current, but also on the clearing time of the protective device, the assumption of an infinite source on the transformer primary will not guarantee the most conservative results for incident energy calculations downstream of the transformer. This paper examines the effect of utility available fault current on incident energy calculations and provides the study engineer with a list of reasonable assumptions that can be made in the event that actual utility fault information is not available.**

Index Terms – Short-Circuit Study, Arc-flash Analysis, Incident Energy, Utility Available Fault Current, Infinite Bus Assumption

I. INTRODUCTION

The safety requirements of industry standards [1,2] and increased awareness of arc-flash hazard demand incident energy calculations be performed for all equipment locations where energized electrical work is performed. It is crucial that information about the existing system configuration is obtained and modeled accurately to get the most accurate arc-flash hazard results.

One of the most important pieces of information needed to do an arc-flash hazard analysis is the available fault current data from the utility at the point of interconnection, as the subsequent fault currents at different equipment locations in a facility are calculated based on this information. Whenever the utility is unable to provide this data for a facility, it is common practice to assume an infinite bus at the primary side of the service transformer to complete the analysis. Though this approach yields maximum arcing fault current at a location, it could falsely decrease the arcing time in the calculations. Consequently, the calculated Personal Protective Equipment (PPE) requirement may not be adequate to protect the personnel in the event of an arc flash.

The objective of this paper is to demonstrate that using an infinite bus assumption does not yield conservative arc-flash results and to bring awareness to the power industry about the difficulty in obtaining utility fault current information.

This paper will first discuss the basics of short-circuit and incident energy calculations and showcase the impact of available fault currents on incident energy calculations for four sample systems. It will then introduce a novel technique to use in the absence of actual utility fault current information. This technique will be applied to ten real projects and the results will be compared to the arc-flash results based on actual utility fault current information to test its effectiveness.

II. SHORT-CIRCUIT CURRENT CALCULATIONS

IEEE Std 399-1997 (Brown Book) [3] and IEEE Std 141-1993 (Red Book) [4] detail the recommended practices for performing short-circuit studies. The Brown Book presents the main reasons for performing short-circuit studies as the following:

- Verification of the adequacy of existing interrupting equipment. The same type of studies will form the basis for the selection of the interrupting equipment for system planning purposes.
- Determination of the system protective device settings, which is done primarily by quantities characterizing the system under fault conditions. These quantities also referred to as “protection handles,” typically include phase and sequence currents or voltages and rates of changes of system currents or voltages.
- Determination of the effects of the fault currents on various system components such as cables, lines, busways, transformers, and reactors during the time the fault persists. Thermal and mechanical stresses from the resulting fault currents should always be compared with the corresponding short-term, usually first-cycle, withstand capabilities of the system equipment.
- Assessment of the effect that different kinds of short circuits of varying severity may have on the overall system voltage profile. These studies will

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- identify areas in the system for which faults can result in unacceptably widespread voltage depressions.
- Conceptualization, design and refinement of system layout, neutral grounding, and substation grounding.

Following these guidelines, it is common practice to perform short-circuit studies based on the worst-case fault current that an electrical system may experience in its lifetime.

III. MAKING CONSERVATIVE ASSUMPTIONS

Fault current flows from the source(s) of power through the power system impedance to the fault location. The most common sources of fault current are:

- Utility Systems
- Rotating Machines (Generators and Motors)

The most common power system impedance components are:

- Transformers
- Conductors

The magnitude of the fault current is determined by the combination of sources and impedances between the sources to a location in the power system where a fault might occur. Knowing the effect that sources and impedances have on fault calculations allows the study engineer to make assumptions that will result in conservative results when actual system data is unavailable.

From a utility perspective, a conservative assumption for the available fault current at a customer's facility corresponds to an infinite source on the primary of the service transformer. Assuming an infinite source helps ensure that changes in the utility system, such as various switching conditions, line reconfiguration, substation and/or generation construction or upgrades will not effect the short-circuit ratings of equipment within an end-user's electrical distribution system.

The maximum three-phase bolted fault current at the secondary side of a transformer is calculated using the following equations [2]:

$$I_{scsym} = \frac{E_{pu}}{Z_{pu}} \cdot I_{base} \quad (1)$$

$$I_{base} = \frac{kVA_t}{\sqrt{3}kV_{LL}} \quad (2)$$

where I_{scsym} is a three-phase symmetrical first cycle bolted short-circuit rms current, E_{pu} is the pre-fault operating voltage, Z_{pu} (for convenience, only reactive portion is used, i.e. $Z_{pu} = X_{pu}$) is the equivalent per-unit (p.u.) impedance of the system on the transformer base kVA, kVA_t is the transformer nominal kVA rating and kV_{LL} is the line-to-line voltage at the secondary side of the transformer. For Sample system 1 in Fig. 1, $Z_{pu} = X_{u-1} + X_t$, where X_{u-1} and X_t are the per-unit impedances of the utility and service transformer respectively. For an infinite bus at the primary side of the transformer, $X_{u-1} = 0$ and hence $Z_{pu} = X_t$.

The maximum three-phase bolted fault current at the location designated 480V SWGR in Sample system 1 can be calculated based on the transformer T-UTILITY-1's impedance as follows:

$$I_{bf,max,sec} = \frac{1}{0.0575} \cdot \frac{2000}{\sqrt{3} \cdot 0.48} = 41.8\,kA$$

Table I lists the changes in fault current at 480V SWGR for different source impedance values at the utility side. For example, if the actual source impedance is 0.0246 p.u. (X_u) on the transformer base, the available fault current at 480V SWGR becomes

$$I_{bf,sec,70\%} = \frac{1}{(0.0246 + 0.0575)} \cdot \frac{2000}{\sqrt{3} \cdot 0.48} = 29.3\,kA$$

The actual fault current at 480V SWGR is about 70% of the estimated maximum secondary fault current ($I_{bf,max,sec}$) because of the added source impedance.

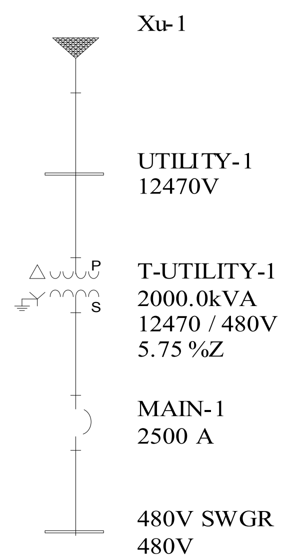

Fig. 1 Sample system 1

TABLE I
IMPACT OF SOURCE IMPEDANCES ON FAULT CURRENT

Short-Circuit primary			**SC sec**	**% of**
(MVA)	**(kA)**	**Xu (p.u.)**	**(kA)**	$\mathbf{I_{bf,max,sec}}$
3.86	0.18	0.5175	4.18	10%
8.70	0.40	0.2300	8.37	20%
14.91	0.69	0.1342	12.55	30%
23.19	1.07	0.0863	16.73	40%
34.78	1.61	0.0575	20.92	50%
52.17	2.42	0.0383	25.10	60%
81.16	3.76	0.0246	29.29	70%
139.13	6.44	0.0144	33.47	80%
313.04	14.49	0.0064	37.65	90%
Infinite		0.0000	41.84	100%

The impact of changes in primary fault current on secondary fault current for the entire range of fault currents at 480V SWGR are plotted in Fig. 2.

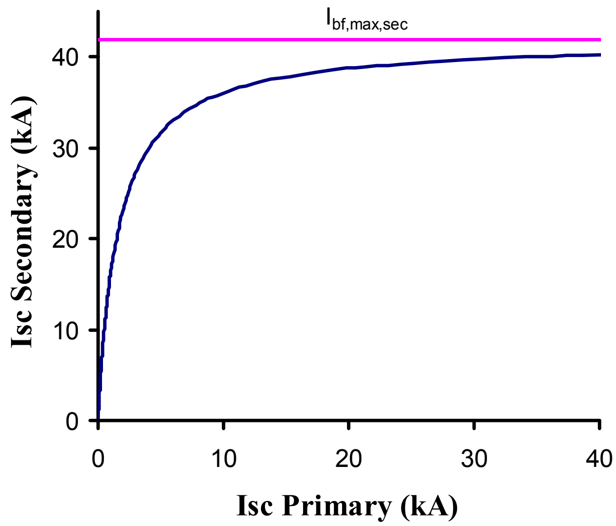

Fig. 2 Impact of changes in primary fault current to secondary fault current of a transformer

IV. INCIDENT ENERGY CALCULATIONS

There are several methods available for performing arc flash hazard analysis to calculate incident energy. Some of these methods are summarized in Annex D of [1] and the effectiveness and merit of each method is compared in [5]. IEEE Std 1584-2002 [6] is one of the accepted methods of conducting an arc-flash hazard analysis and will be used in this paper. This method uses equations that were developed using statistical analysis of data from arc-flash testing performed at laboratories. During testing, it was shown that the incident energy was dependent on the following main factors:

- Available fault current at the fault location
- Protective device clearing time
- Equipment and installation type
- Working distance from the arc

The equations from IEEE Std 1584-2002 [6] are given below to explain the impact of bolted fault current on incident energy calculations in the sample system.

For applications with a system voltage under 1000 V solve the equation (3):

$$\lg I_a = K + 0.662 \lg I_{bf} + 0.0966V + 0.000526G + 0.5588V(\lg I_{bf}) - 0.00304G(\lg I_{bf}) \quad (3)$$

where

- lg is the log10.
- 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).

For applications with a system voltage of 1000 V and higher solve the equation (4) and (5) to determine the arcing current:

$$\lg I_a = 0.00402 + 0.983 \lg I_{bf} \quad (4)$$

Convert from lg:

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

Calculate a second arcing current equal to 85% of I_a so that a second arcing duration can be determined.

For each arcing current, find the log10 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.

$$\lg E_n = K_1 + K_2 + 1.081 \lg I_a + 0.0011G \quad (6)$$

where

- E_n is incident energy (J/cm2) normalized for time and distance
- 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)

$$E_n = 10^{\lg E_n} \quad (7)$$

Finally, convert from normalized to determine the incident energy for the 100% and 85% arcing current values:

$$E = C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{610^x}{D^x}\right) \quad (8)$$

where

- E is incident energy (cal/cm^2)
- 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
- T is arcing time (seconds)
- D is distance from the possible arc point to the person (mm)
- x is the distance exponent.

It is evident that for any given system, typical working distances and the types of equipments will remain constant and the incident energy will change for any variations in the available fault current. Any change in available fault current also changes the arcing current and the corresponding tripping time of the protective devices. Based on this and the calculations at Table I, it can be concluded that when performing incident energy calculations, the impact of primary fault current is significant when the fault current at the secondary side of a transformer is smaller (X_u>>X_t). As the fault current at the secondary side of a transformer approaches the maximum (X_u<<X_t), the impact of changes in primary fault current becomes insignificant.

V. SAMPLE SYSTEMS

Four sample systems are chosen to represent the typical equipments found in the distribution systems. All of the sample systems are assumed to be solidly grounded on the secondary side of the service transformer.

1. 480 V switchgear fed from a 2500 kVA transformer with 2500 A static trip main circuit breaker. (Fig. 3)
2. 480 V panel board fed from a 500kVA transformer with a 600 A thermal magnetic main circuit breaker. (Fig. 3)
3. 4160 V motor control center fed from a 5000kVA transformer with a 600 A main fuse. (Fig. 3)
4. 13.8 kV switchgear fed from a 10,000 kVA transformer protected by an over-current relay. (Fig. 3)

The time-current characteristics of the protective devices in sample systems are provided in Fig. 4. Arc-flash hazard analysis calculations were performed for these four sample systems based on different utility fault current values (10% through 100% of maximum secondary fault current ($I_{bf,max,sec}$) of the utility transformer) the results are presented in Table II. The values are also plotted in Fig. 5.

TABLE II
INCIDENT ENERGY CALCULATIONS FOR DIFFERENT AVAILABLE UTILITY FAULT CURRENTS

% of $I_{bf,max,sec}$	Incident Energy (cal/cm^2)			
	Sample System1	Sample System2	Sample System3	Sample System4
10%	11.7	5.2	2.3	1.5
20%	21.8	9.9	4.9	3.2
30%	31.4	14.4	7.5	4.9
40%	40.6	18.8	10	6.7
50%	41.7	23.1	13	7.5
60%	8.8	23.0	8	6.7
70%	10.1	1.1	5.2	6.4
80%	11.4	1.1	3.6	6.1
90%	12.7	1.1	2.7	6.1
100%	13.9	1.2	2.1	6.1

Due to the inverse time-current tripping characteristics of these protective devices, higher fault currents would be cleared much quicker than lower fault currents. For example in the sample system 1, arcing currents calculated based on the fault currents from 60% to 100% of $I_{bf,max,sec}$, would be cleared with a delay of 0.3 s while it would take more than 2 s to clear any fault with lower fault current than 60% of $I_{bf,max,sec}$. In such instances, the incident energy was calculated for maximum arcing time of 2 s as per [6]. This has caused the incident energy values using infinite bus assumption (100%) to be much lower than the values of 50% $I_{bf,max,sec}$ scenario. Similar results were obtained in sample system 2, as the maximum arcing time was reached for 50% of $I_{bf,max,sec}$. It is important to note that arcing time was determined based on the arcing currents calculated as per equation 4. A circuit breaker opening time of 5 cycles was added to the arcing time calculations in sample system 4.

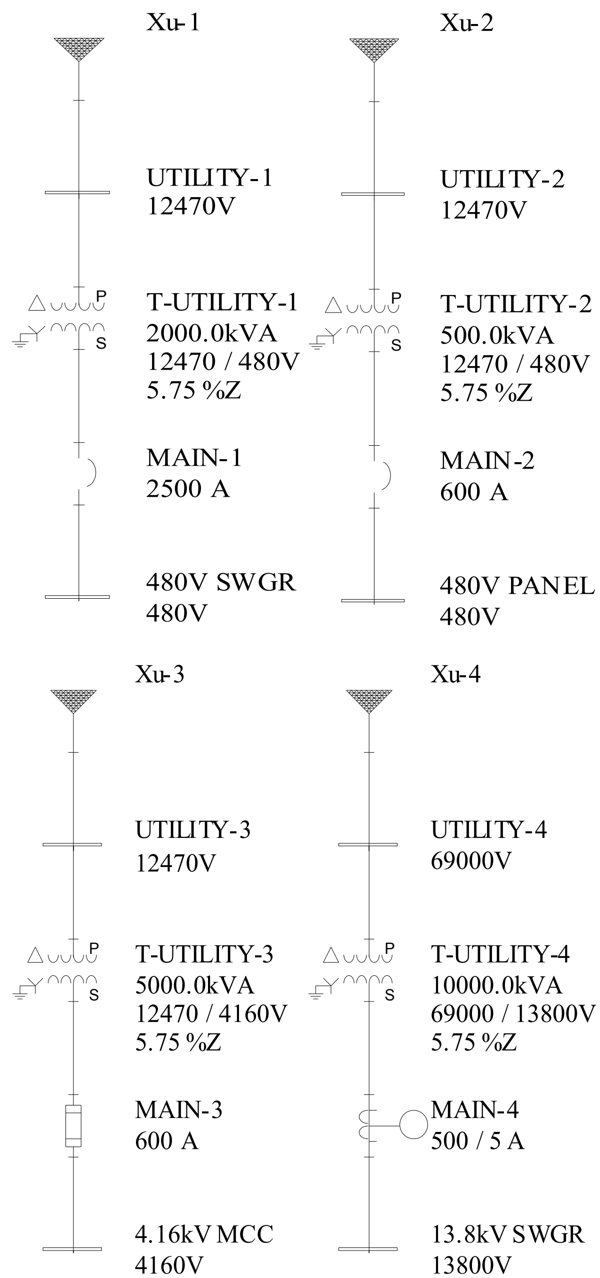

Fig. 3 Sample Systems 1, 2, 3 and 4

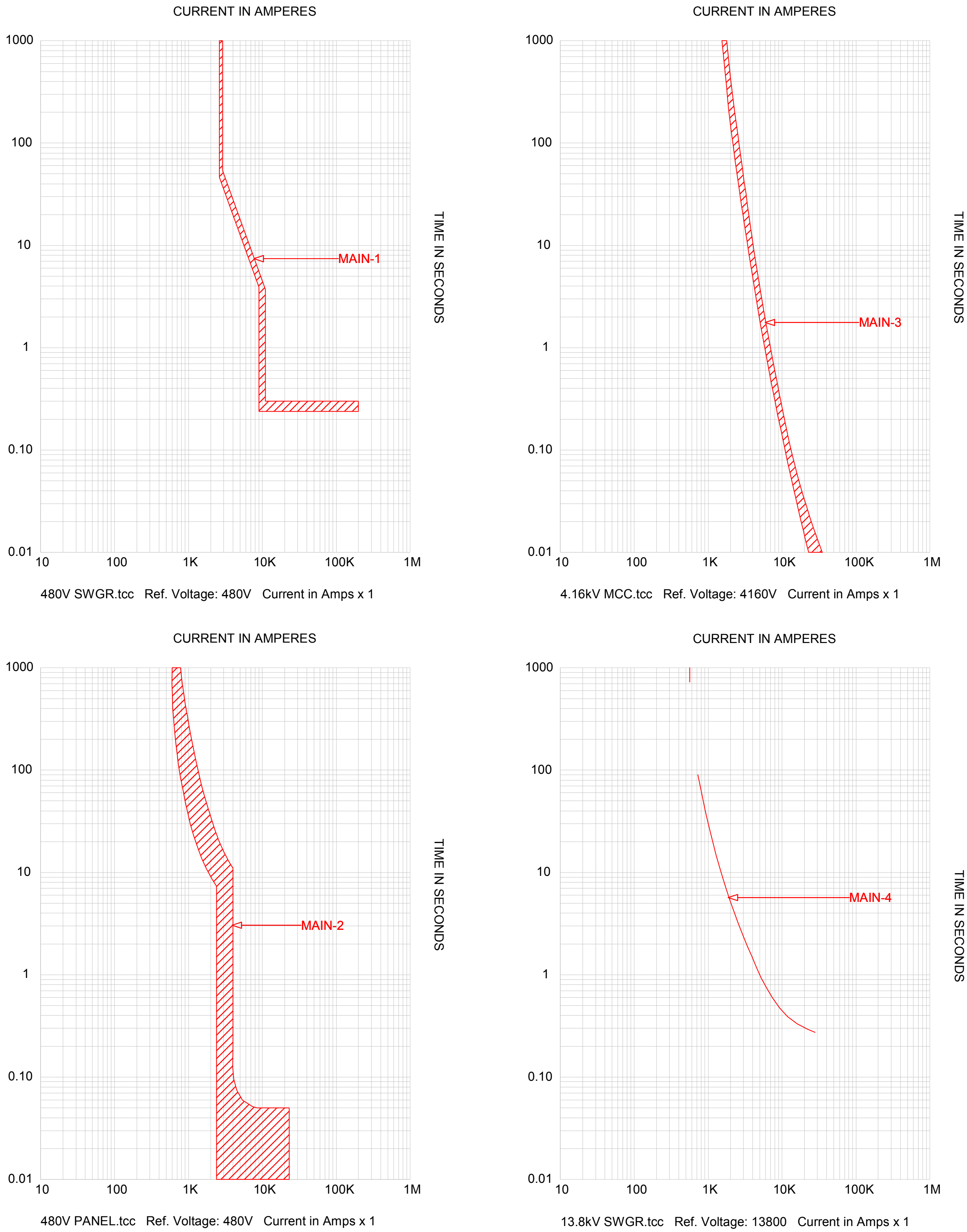

Fig. 4 Time Current Characteristics of the main protective devices in sample systems 1 through 4

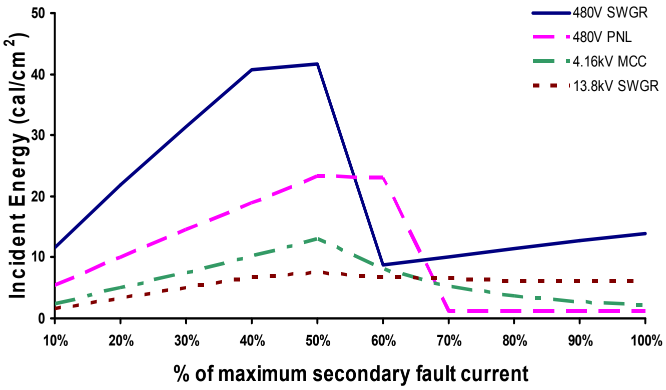

Fig. 5 Impact of fault current on incident energy calculations

Since the fuse and the over-current relay in sample systems 3 and 4 did not have short-time and instantaneous sections like the breakers in sample systems 1 and 2, the incident energy declined steadily until it reached maximum arcing time. This happened at 50% $I_{bf,max,sec}$ scenario for both the systems, after which the arcing current was too low that even with maximum arcing time, the incident energy couldn't reach the level of 50% $I_{bf,max,sec}$ scenario. As illustrated by Fig. 5, the incident energy calculations based on an infinite bus assumption did not produce worst case arc-flash results when compared to other fault current scenarios (10% through 90% of $I_{bf,max,sec}$) in all four sample systems.

The incident energy calculations were higher for the following two criteria in the four sample systems:

1. High fault current, consequently high arcing current
2. High arcing time

IEEE Std 1584 – 2002 [6] recommends that maximum and minimum fault currents be obtained from the utility for various switching conditions and the worst case PPE requirement should be selected from both the scenarios. A similar approach is needed in the absence of actual utility fault current data. One scenario needs to be done based on infinite bus assumption to meet the criteria no. 1 and another scenario based on 50% of maximum secondary fault current at the utility transformer to meet the criteria no. 2. The PPE requirement needs to be selected from the worst case between these two scenarios.

VI. CASE STUDIES

Ten different types of projects were chosen to compare the arc-flash results based on actual fault current data and the maximum fault current data. The ratio of available fault current to the maximum secondary fault current for all the projects are shown in Table III. Some projects had two incoming utility lines and each of them was compared to the corresponding utility transformer rating. A wide range of utility fault currents were chosen to test this approach.

TABLE III
AVAILABLE FAULT CURRENT IN % OF MAXIMUM SECONDARY FAULT CURRENT ($I_{bf,max,sec}$) BASED ON SERVICE TRANSFORMER DATA

Project #	Utility 1 (%of $I_{bf,max,sec}$)	Utility 2 (%of $I_{bf,max,sec}$)
1	81.2%	-
2	74.6%	-
3	61.1%	85.0%
4	61.6%	47.4%
5	74.3%	-
6	76.5%	-
7	90.0%	-
8	58.5%	-
9	68.2%	-
10	89.2%	89.2%

The PPE requirements were calculated for all the locations based for the following three scenarios.

1. Scenario 0: Incident energy calculations using actual utility data
2. Scenario 1: Incident energy calculations using infinite bus assumption
3. Scenario 2: Incident energy calculations using 50% of the maximum secondary fault current at the utility service transformer. It is achieved when $X_u = X_t$.

The results from Scenarios 1 and 2 were compared with results from Scenario 0 in Table IV and V respectively. It is clear from Table IV that using an infinite bus assumption did not yield conservative arc-flash results for all locations when compared to the actual fault current results. The same is also true for Scenario 2 (Table V). When the worst case PPE requirements from Scenarios 1 and 2 were used (Table VI), the results were always conservative compared to Scenario 0.

For example, if incident energy calculations were performed using infinite bus assumption (Scenario 1) in Project 5, the results would have required inadequate PPE at 4.3% of the bus locations when compared to the arc-flash results based on actual utility fault current (Scenario 0). Using 50% of $I_{bf,max,sec}$ (Scenario 2) would have required inadequate PPE at 8.7% of the bus locations compared to Scenario 0. If worst-case (higher) PPE requirement of Scenarios 1 and 2 were chosen at each bus, the results would have required adequate or higher PPE at all the locations.

There is a possibility that when the utility available fault current is very low (<50% of $I_{bf,max,sec}$, possible at remote locations), neither of these two scenarios could produce conservative results. In such cases, the worst case PPE requirements based on Scenarios 1 and 2 would likely be closer to the actual values than using the results from Scenario 1 alone.

TABLE IV
ARC-FLASH RESULTS OF SCENARIO 1 VS. SCENARIO 0

Project #	AF results using infinite bus assumption were		
	conservative	not sufficient	equal
1	7.1%	14.3%	78.6%
2	-	-	100.0%
3	-	15.8%	84.2%
4	-	10.0%	90.0%
5	10.9%	4.3%	84.8%
6	-	8.3%	91.7%
7	0.9%	-	99.1%
8	0.6%	6.3%	93.1%
9	8.7%	-	91.3%
10	-	8.3%	91.7%

TABLE V
ARC-FLASH RESULTS OF SCENARIO 2 VS. SCENARIO 0

Project #	AF results using 50% of $I_{bf,max,sec}$ were		
	conservative	not sufficient	equal
1	21.4%	-	78.6%
2	10.0%	-	90.0%
3	21.1%	-	78.9%
4	-	-	100.0%
5	8.7%	8.7%	82.6%
6	6.3%	-	93.8%
7	4.7%	6.5%	88.8%
8	-	0.6%	99.4%
9	-	-	100.0%
10	16.7%	8.3%	75.0%

TABLE VI
ARC-FLASH RESULTS FOR WORST CASE OF SCENARIO 1 AND 2 VS. SCENARIO 0

Project #	Worst case PPE of Scenarios 1 and 2 were		
	conservative	not sufficient	equal
1	28.6%	-	71.4%
2	10.0%	-	90.0%
3	21.1%	-	78.9%
4	-	-	100.0%
5	15.2%	-	84.8%
6	6.3%	-	93.8%
7	5.6%	-	94.4%
8	1.1%	-	98.9%
9	8.7%	-	91.3%
10	16.7%	-	83.3%

VII. ARC-FLASH HAZARD ANALYSIS SURVEY

A survey was conducted among 42 study engineers about the arc-flash hazard analysis they performed in the last twelve (12) months to find out the trend in using infinite bus assumption. The results of this survey are presented in Table VII. It was alarming to find out that more than half of the respondents (57%) have used infinite bus assumption to complete arc-flash hazard analysis at least once in the last 12 months and 17% of their studies were performed using infinite bus assumption. It is also disturbing to learn that 34% of the respondents claimed “utility company refused to provide the actual fault current data” as the top reason to use infinite bus assumption. The survey has shown that obtaining realistic fault current data from the utility have become increasingly difficult and it has become a common practice to use infinite bus assumption.

TABLE VII
RESULTS OF THE ARC-FLASH HAZARD ANALYSIS SURVEY

% of people who have used infinite bus assumption at least once in the last 12 months	**57%**
Total number of studies performed in the last 12 months	**539**
% of Studies using Maximum AND Minimum Fault Current information	20%
% of Studies using Maximum OR Minimum Fault current information	63%
% of Studies using infinite bus assumption	17%
Top Reasons to perform arc-flash study using infinite bus assumption	
Utility company didn't have actual fault current information	34%
Utility company refused to provide the fault current information	34%
Difficulty Level in obtaining utility fault current information	
Easy	2%
Moderate	64%
Difficult	34%

VIII. CONCLUSION

When utility cannot provide fault current data, IEEE Std. 1584 – 2002 [6] suggests requesting public utility commissions to require utility companies to provide realistic fault current data. It is recommended that public utility commissions provide guidelines to the utility companies similar to NEMA [7] to educate the utility companies about the impact of actual fault current on arc flash hazard calculations and make the process of obtaining this information easier.

This paper has demonstrated that performing an arc-flash hazard analysis using only an infinite bus scenario does not provide the most conservative results for all equipment locations. When no fault current information is available from the utility, the arc-flash hazard analysis should include a second scenario where 50% of $I_{bf,max,sec}$ is used as the available fault current from the utility. The worst-case arc-flash results between these two scenarios should be used as a conservative value to choose PPE to protect the personnel. This conclusion was established using the arc-flash results from four sample systems and ten real-life arc-flash hazard analysis projects.

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X. VITAE

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