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ORIGINAL RESEARCH ARTICLE

ARC FLASH STUDY OF IEEE 8 BUS TEST SYSTEM USING DIGITAL SIMULATION AND ELECTRICAL NETWORK ANALYSIS PLATFORM

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ABSTRACT

Nowadays, electricity plays an important role in our life and in our industries. However, when an arc fault occurs, it creates an incident that can cause a serious damage to the equipment and can cause serious injury to the workers. Arc fault is generated when electric current passes through air from one uncovered live conductor to another or to ground in electrical system. Analyzing the level of arc flash and providing a good protection to the workers is paramount. In this work DigSILENT software was used to study the Arc Flash of Institute of Electrical and Electronics Engineers (IEEE) 8 Bus Test System. Firstly, a model of system was created in the DigSILENT environment and then arc flash study of all the buses in the system was carried out. Based on the simulation results obtained, Personnel protective equipment and labels were generated to inform the workers about the level of danger they are exposed to in the course of doing their work. The risk category for buses numbers 3 and 7 are cat 2 and 3 respectively while for buses 1and 5 and for buses 2,4,6 and 8 are cat 4 and 5 respectively. The results showed that there is a need for the personnel to equip themselves with the appropriate Personnel Protective Equipment (PPE) as suggested before access. Because, arc flash faults have significant effect on personnel and equipment. It's really important for stability, energy continuity, human life and economy.

1.0 Introduction

An arc flash is an explosive burst of light and heat produced as part of an arc fault, a type of electrical explosion or discharge that results from a connection through air to ground or another voltage phase in an electrical system. The results are often violent and when a human is in close proximity to the arc flash, serious injury and even death can occur. Arc flash can be caused by many things including: dust, dropping tools, accidental touching, condensation, material failure, corrosion, faulty installation (Yadav and Harith, 2016).

An Arc Flash study is a risk assessment of a workplace environment that determines Arc Flash hazards. It is important that an expert in electrical safety conducts an assessment to ensure that a company understands the risks their workplace poses to their personnel and how to protect them against it. The severity of an arc flash injury is caused by the temperature, fault current and time for circuit breaker to operate and closeness of the object to the danger zone. These zones are: flash protection limits, limited zone, restricted zone, prohibited zone.

Arc Flash analysis requires the completion of a Short Circuit Study and a Coordination Study. The results of the Arc Flash calculations are based on the calculated values of fault current magnitudes found in the short circuit study and the associated clearing times of overcurrent protection devices as determined by the coordination study (Valdes and Floyd, 2021).

This study is aimed at determining the incident energy potentially present during an arc flash event. The magnitude of the incident energy is calculated on the basis of the available fault current, the clearing time of associated system protection, and the physical parameters of the system location. Associated with this calculation is the determination of an approach distance within which the incident energy level is above 1.2 cal/cm2 (Quincy, 2015). Appropriate Personal Protection Equipment (PPE) shall be used when working on or near energized equipment within the lash protection boundary (Gammon et al., 2015).

Results of the study may be displayed in labels on equipment enclosures to inform and direct facility personnel with respect to the potential arc flash hazard.

2. Review of Arc Flash Analysis Standards

National Fire Prevention Agency (NFPA) 70E-2000 edition, makes it necessary for facility personnel to wear PPE when carrying out various tasks in areas liable to potential Arc Flash Hazards Standard for Electrical Safety in the Workplace (2015). These requirements were made necessary on the basis of field experience and are categorized by associated voltage levels. The Hazard Category is determined by the nature of the work to be completed, the operating voltage, and the available short circuit current for that general location in the electrical distribution system. The Hazard Category refers to the appropriate protective clothing and the PPE to be utilized.

IEEE Standard 1584™ – 2002 describes the procedures and provides direction for an accurate means of determining a safe Arc Flash Boundary and associated Hazard Level (Nagsarkar and Sukhija, 2011).

The basis for this method is experimental data recorded from simulated arcs corresponding to bolted, three-phase fault current magnitudes measured at the terminals of an experimental enclosure (Short, 2011). The categories of PPE as described in NFPA 70E are summarized in Table 1:

Table 1: Categories of PPE, Reddy and Satyanarayana (2018).

S/No.	Risk Category	Clothing Description (Number of Layers)	Rating of PPE (cal/cm^2)
1.	1	Flame Resistant shirt and Flame-Resistant pants or Flame-Resistant coveralls (1 layer)	4
2.	2	Cotton underwear plus Flame Resistant shirt and Flame-Resistant pants (1 or 2 layers)	8
3.	3	Cotton underwear plus Flame Resistant shirt and Flame-Resistant pants plus Flame Resistant coveralls, or Cotton underwear plus two Flame Resistant coveralls (2 or 3 layers)	25
4.	4	Cotton underwear plus Flame Resistant shirt and Flame-Resistant pants plus multilayer flash suit (3 or more layers)	40
5.	5	Cotton underwear plus Flame Resistant shirt and Flame-Resistant pants plus multilayer flash suit (4 or more layers)	48

2.1 NFPA 70E and IEEE 1584 Equations for Arc Flash Calculations

Normalized incident energy can be found using equation (1) (Gopila, 2021).

$$E_n = K_1 + K_2 + 1.081 \times \log I_a + 0.001 \times G_B \quad (1)$$

Where,

En - incident energy in J/cm 2 normalized for time and distance. The equation above is based on data normalized for a distance from the possible arc point to the person of 610 mm and an arcing time of 0.2 sec

K_1 = -0.792 for open configurations, and is - 0.555 for box configurations or enclosed equipment

K_2= 0 for ungrounded and high resistance grounded systems and equals - 0.113 for grounded systems

G_B- gap between conductors in millimeters

Ia - predicted three phase arcing current in kA. It is found by using Equations 2 or 3 so the operating time for protective devices can be determined.

For 1000V and lower systems (Rubini and Krishnakumar, 2020),

$$logI_a = K + 0.662 \times logI_{bf} + 0.0966 \times V + 0.000526 \times G_B + 0.5588\ V \times logI_{bf} - 0.00304 \times logI_{bf} \quad (2)$$

where:

Log is logarithm base 10 (log10)

Ia - arcing current in kA

K is equal to - 0. 153 for open configurations. and - 0.097 for box configurations

$logI_{bf}$ is bolted fault current for three phase faults in kA symmetrical rms

V- system voltage in kV

G_B - gap between conductors in millimeters.

where:

$$logIa = 0.00402 + 0983 \times logI_{bf} \quad (3)$$

For applications with a system voltage ranging from 1 up to 15kV

Incident energy can be found using the equation (4):

$$E = 4.184 \times C_f \times E_n \times \left(\frac{t}{0.2}\right) \times \left(\frac{610^X}{D^X}\right) \quad (4)$$

where:

E is incident energy exposure in J/cm^2

C_f is calculation factor equal to 1.0 for voltages above 1 kV, and 1.5 for voltages below 1 kV

$E_n$is normalized incident energy in J/cm^2 as calculated by Equation (1).

t is arcing time in seconds

D is distance from possible arcing point to the person in millimeters

x- distance exponent.

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 incident energy can be determined using the equation 5:

$$E = 2.142 \times 10^6 \times I_{bf} \times \left(\frac{t}{D^2}\right) \tag{5}$$

Where:
E is incident energy in J/cm^2
V is system voltage in kV
t is arcing time in seconds
D is distance from possible arc point
For the IEEE Std 1584-2002 empirically derived model, arc flash boundary is calculated using the equation 6 (Yadav and Harit, 2016).

$$D_B = \left[4.18 \times C_f \times E_n \times \left(\frac{t}{0.2}\right) \times \left(\frac{610^X}{D_B}\right)\right]^{\frac{1}{X}} \tag{6}$$

For the Lee method:

$$D_B = \left[2.142 \times 10^6 \times V \times I_{bf}\left(\frac{t}{E_B}\right)\right]^{\frac{1}{2}} \tag{7}$$

where:
D_B is distance of the boundary from the arc point in millimeters
C_f is calculation factor equal to 1.0 for voltages above 1 kV and 1.5 for voltages below 1 kV
En is normalized incident energy in J/cm^2 as calculated by Equation (1)
E_B is incident energy in J/cm^2 at the boundary distance. It is usually set at 5 J/cm^2 (1.2 cal/cm^2) for bare skin or at the rating of proposed personal protection equipment.
I_{bf} is bolted fault current for three phase faults in kA symmetrical rms
t is arcing time in seconds and x is distance exponent.

3.0 Materials and Methods

3.1 Collection of input Data

Single Line Diagram (Figure 1), equipment parameters (Voltage kV rating, Power MVA rating, Impedance, System fault level, X/R ratio, protection settings) of the Substation were collected. Electrode configuration of the panel based on IEEE 1584 such as VCB, VCBB, HCB, VOA, HOA gear for the worst scenario were checked.

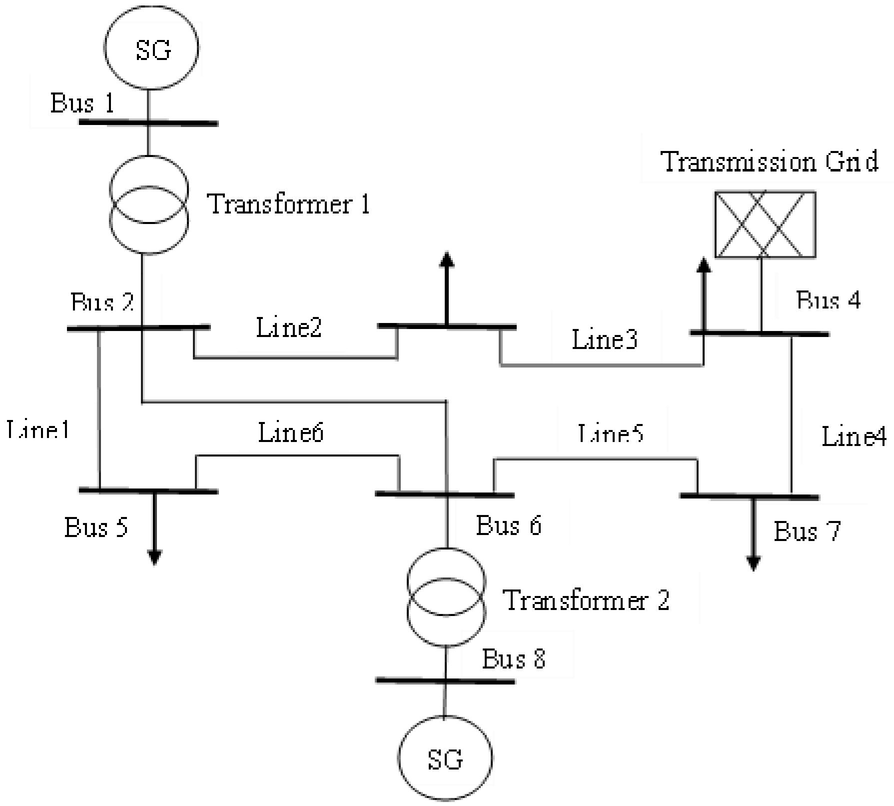

Figure 1: Single line Diagram of the IEEE 8 Bus test system (Reddy and Satyanarayana, 2018)

3.2 Digital Simulation and Electrical Network Analysis Platform

DigSILENT Stands for Digital simulation and electrical network analysis software. It is a leading power system analysis software application for use in analyzing generation, transmission, distribution and industrial systems.

It covers the full range of functionality from standard features to highly sophisticated and advanced applications including wind power, distributed generation, real-time simulation and performance monitoring for system testing and supervision. DigSILENT is easy to use, fully Windows compatible and combines reliable and flexible system modelling capabilities with state-of-the-art algorithms and a unique database concept. Also, with its flexibility for scripting and interfacing, DigSILENT is perfectly suited to highly automated and integrated applications.

DigSILENT has a quick incident energy calculator, which is powerful analysis tool that allow user to perform a quick Arc Flash analysis at the bus level when the following input data necessary to perform AFH analysis are available (Doughty et al., 2000).

Short circuit current (kA) at all the buses after short circuit study.
Fault Clearing Time (FCT) in (sec).
Gap between conductors (mm).
Working distance (mm).
Equipment type (Gumilar, 2020).

3.3 Modelling and Simulation

IEEE 8 Buses test system was modelled and simulated for Arc Flash and Hazard (AFH) analysis using DigSILENT. It has an integrated module for AFH analysis based on IEEE 1584 and NFPA 70E.

The arc fault current, duration of arc fault current based on protection settings/relay coordination, incident energy for each bus at the working distance and suitable PPE were analysed as follows.

Firstly, power flow study was carried out on the substation to optimize circuit loading condition and to keep system voltages within specified limits. Power system are prone to occurrence of fault which causes interruption of power supply from generating station to the load centers as a result providing protection against electrical faults grounding is necessary in electrical systems (Lee, 1987).

Secondly, short circuit study was carried out to determine bolted fault current value (Ibf) value at each bus which was further used to find out the arcing current (Ia), incident energy E and Arc Flash Boundaries.

Thirdly, protective devices settings and coordination was done for proper sequential tripping of protective devices (PDs) near the faulted bus and to keep unprotected areas less affected by faulty condition. Protective device coordination is important part of arc flash analysis as it formed part equations used to find out fault clearing time of each PDs which is further used to find out incident energy E and Arc Flash Boundaries (AFB) in AFH analysis (Dass, 2020).

Fourthly, Danger and warning labels were generated based on the results obtained.

Finally, Detailed report including labels were presented in Tables 2 to 6 and Figures 2 to 6.

3.4 System Description

IEEE 8 Buses test system has two Generators rated 150 MVA, 10 kV, two transformers rated 150 MVA, 10/150 kV and Bus 4 is connected to external gid of 400 MVA. Load of 20 MW and 40 MVar, 60 MW and 40 MVar, 70 MW and 40 MVar, 70 MW and 50 MVar were connected to nodes 2,3,4 and 5 respectively. The total line length of the system is 650 Km, Figure 1 depicts the single line diagram of the system and Figure 2 presents the model of the system in Digsilent (Bharti, 2020).

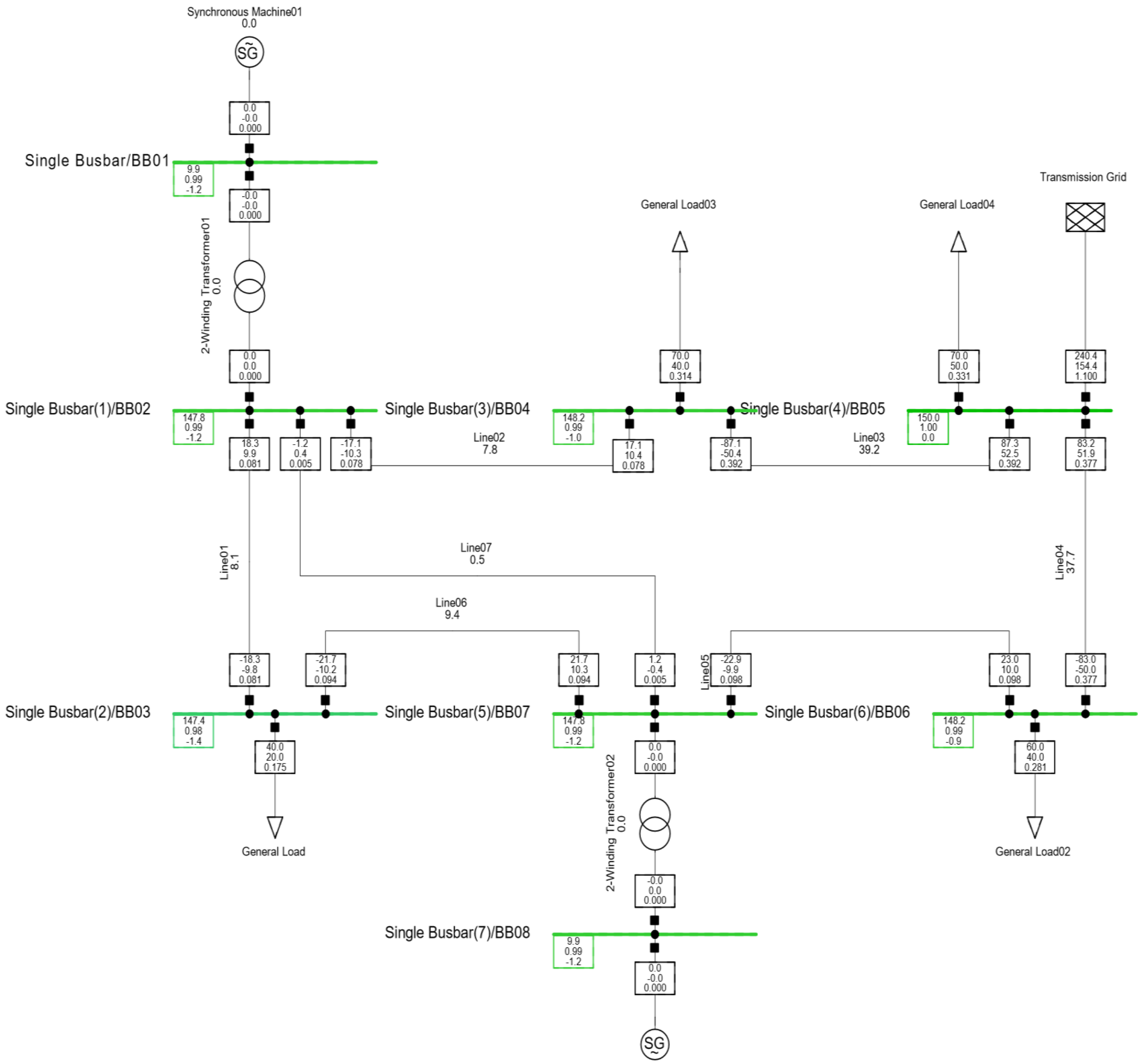

Figure 2: IEEE 8 Buses Test System in Digsilent Environment

4. Results and Discussion

Load flow study was carried out as a first step on IEEE 8 bus test system to ensure optimal circuit loading and to keep system voltages within specified limits. Many types of faults occur in substation which causes discontinuous power supply from generating to the load center. For providing protection against electrical faults grounding is necessary in electrical systems. Then after short circuit study was carried out to determine bolted fault current value (Ibf) value at each bus which is used to find out the arcing current (Ia), incident energy E and Arc Flash Boundaries.

Protective devices settings and coordination was done for proper sequence tripping of PDs near the faulted bus and keep unprotected areas less affected by faulty condition. Protective device coordination is important part of arc flash analysis to find out fault clearing time of each PDs which is further used to find out incident energy E and Arc Flash Boundaries (AFB) in AFH analysis. The results are as presented in Tables 2 to 7.

Table 2: Load Flow Analysis Results

S/No.	Bus ID	Rated Voltage (kV)	Bus Voltage (kV)	Bus Voltage (P.U)	Angle (Deg)
1.	Bus 1	150	148	0.98	0.00
2.	Bus 2	150	139	0.95	0.67
3.	Bus 3	150	145	0.96	0.54
4.	Bus 4	150	148	0.96	0.45
5.	Bus 5	150	146	0.94	0.65
6.	Bus 6	150	149	0.97	0.22
7.	Bus 7	150	145	0.97	0.32
8.	Bus 8	150	139	0.97	0.23

Table 3: Short Circuit Analysis Results

S/No.	Bus ID	Fault Type			
		LN (kA)	LL(kA)	LLN (kA)	LLL(kA)
1.	Bus 1	37.77	35.74	40.22	39.83
2.	Bus 2	41.63	42.28	44.13	45.84
3.	Bus 3	30.52	29.43	24.74	20.49
4.	Bus 4	25.66	27.54	25.75	50.63
5.	Bus 5	32.39	34.22	34.11	34.82
6.	Bus 6	27.36	23.65	23.67	49.53
7.	Bus 7	26.22	25.87	24.65	43.51
8.	Bus 8	21.71	34.51	31.12	37.88

Table 4: Relay Coordination Results

S/No.	Relay	Plug Setting	TDS
1.	1	0.4644	0.2171
2.	2	1.0728	0.5065
3.	3	0.5681	0.6440
4.	4	0.4553	0.7807
5.	5	0.4861	0.2293
6.	6	1.1828	0.2348
7.	7	0.5468	0.5244
8.	8	0.5518	0.7422
9.	9	0.6187	0.1462
10.	10	0.3648	1.0287
11.	11	0.4392	1.0460
12.	12	0.7757	0.9921
13.	13	0.4754	0.2358
14.	14	0.5058	0.6784

Table 5: Sending and Receiving Ends Fault Current

Primary & Secondary Relay Pairs		Sending End Fault Current (kA)		Receiving End Fault Current (kA)	
Primary Relay No	Secondary Relay No	Primary	Secondary	Primary	Secondary
1	6	32.30	32.30	0.995	0.995
8	9	60.80	11.60	29.90	0.553
8	7	60.80	18.80	29.90	0.078
2	1	59.10	0.993	35.50	39.33
9	10	24.80	24.80	11.60	11.60
2	7	59.10	18.80	35.50	0.746
3	2	35.50	35.50	22.40	22.40
10	11	38.80	23.40	24.80	11.40
6	5	61.00	12.00	32.30	0.626
6	14	61.00	18.70	32.30	0.078
13	8	29.80	29.80	0.986	0.986
14	9	51.90	11.60	18.70	0.151
7	5	52.10	12.00	18..90	0.181
14	1	51.90	0.993	18.70	0.986
7	13	52.10	0.985	18.90	0.994
4	3	37.80	22.40	24.00	10.50
11	12	37.00	37.00	23.40	23.40
5	4	24.00	0.200	12.00	12.00
12	13	58.90	0.985	37.00	0.433
12	14	58.90	18.70	37.00	0.821

AFH analysis results from the global calculation for all the 8 buses are shown in Table 6.
The incident energy depends on the following parameters:

i. Short circuit current

ii. Gap between conductors

iii. Working distance

iv. Fault clearing time

Table 6: Arch Flash Analysis Results.

S/No.	Bus ID	Ibf (kA)	I_a (kA)	E (cal/cm^2)	AFB (m)
1.	Bus 1	34.7	36.4	45.27	34.34
2.	Bus 2	42.2	40.5	50.12	48.65
3.	Bus 3	29.5	27.3	22.77	24.61
4.	Bus 4	34.9	38.2	50.90	41.45
5.	Bus 5	35.1	23.9	46.87	39.92
6.	Bus 6	26.3	37.9	63.67	50.41
7.	Bus 7	38.7	23.2	25.34	26.92
8.	Bus 8	30.6	30.6	64.43	45.78

Plots of the incident energy and the short circuit current at each bus are as presented in Figure 3.

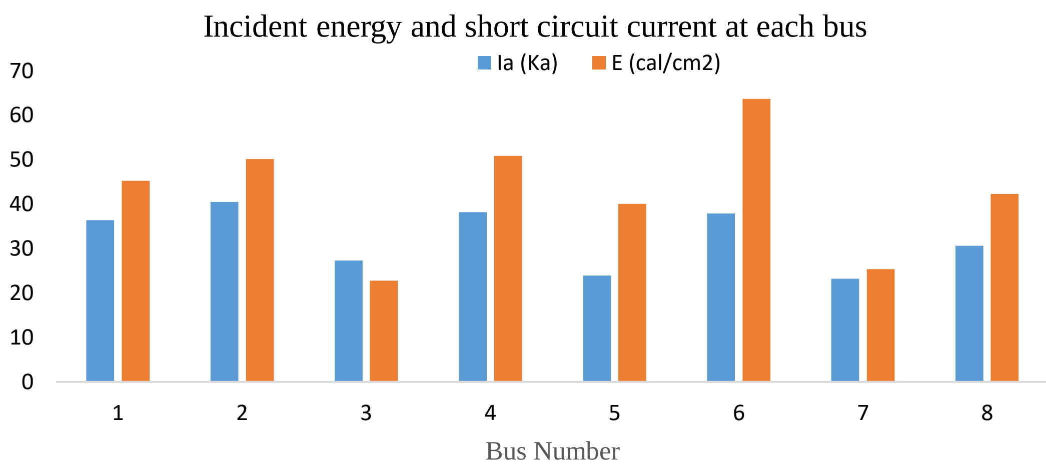

Figure 3: Incident Energy and Short circuit Current at each bus

For all the 8 buses the short circuit current value is different. This value is changed by different ratio and then results are simulated. The incident energy is changed by adjustment in short circuit current at different buses which is shown in Figure 3. When short circuit current increases, arcing current increases which in turn increases the incident energy. From these analyses we can conclude that the fault current is proportional to the incident energy and the short circuit current can be reduced with current limiting fuses and circuit breakers to reduce incident energy. The results of short circuit analysis are presented in Figure 4.

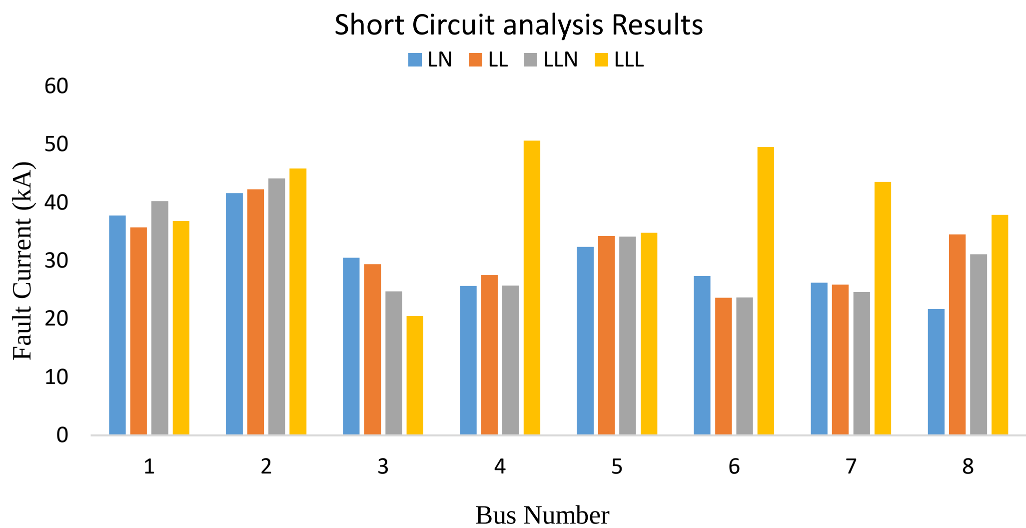

Figure 4: Plot of Fault Currents

Working distance was varied from 500 to 4000 mm in the interval of 500 mm and the results obtained are presented in Figure 4. From the result as the working distance increases the incident energy decreases i.e., there is inverse relation between the two.

Figure 5 depicts the plot of incident energy versus the gap between conductors. Analyzing the plot, it is clear that as the gap between the conductors increases the incident energy also increases. Figure 6 shows that as the fault clearing time increases, incident energy increases while with decrease in fault clearing time incident energy decreases. Hence Fault clearing time reduction is important action to reduce incident energy.

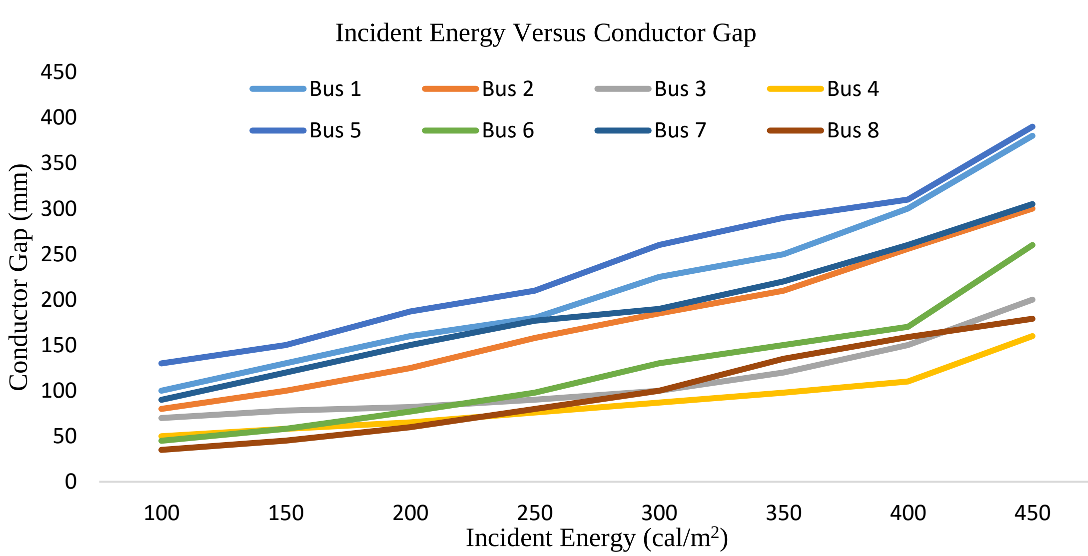

Figure 5: Plot of Incident Energy Versus Conductor Gap

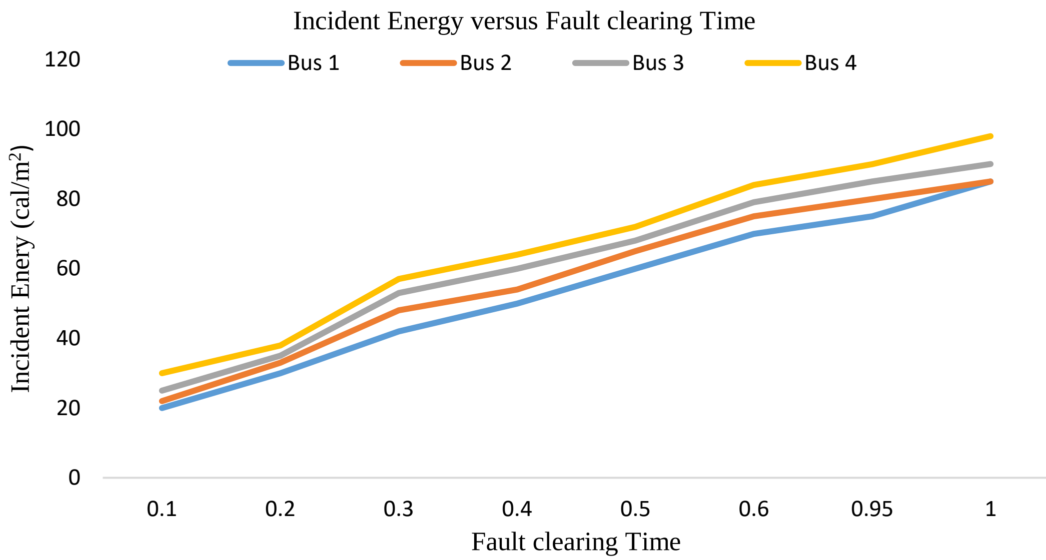

Figure 6: Plot of incident Energy versus Fault Clearing Time

5. Conclusion

In a power system, when an arc fault occurs, it creates an incident that can cause a serious damage to the equipment and can cause serious injury to the workers. Arc fault is generated when electric current passes through air from one uncovered live conductor to another or to ground in electrical system.

In this study efforts have been made to determine the incident energy potentially present during an arc flash event. The magnitude of the incident energy is calculated on the basis of the available fault current, the clearing time of associated system protection, and the physical parameters of the system location. Associated with this calculation is the determination of an approach distance within which the incident energy level is above 1.2 cal/cm^2. Appropriate Personal Protection Equipment shall be recommended to be used when working on or near energized equipment within the protection boundary.

Herein, DigSILENT software was employed to create a model of IEEE 8 Bus test system to carry out the analysis. The study showed that incident energy associated with all the 8 buses are within the range of 22.77 to 64.43 cal/cm^2 which is above the recommended minimum of 1.2 cal/cm^2.

Furthermore, the results showed that the incident energy increases with increase of short circuit current, fault clearing time and gap between conductors while decreases with increase of working distance. In addition, it has been observed that the contribution by three phase bolted fault current is quite high, which can increase the arc fault current. As a result of these, arc flash incident energy on Buses 4 and 7 increased. As stated earlier, arc flash hazard analysis is quite important, therefore correct method of analysis should be used. Because, arc flash faults have significant effect on personnel and equipment. It's really important for stability, energy continuity, human life and economy.

Finally, based on the level of incident energy for each bus, the appropriate PPE has been recommended to be used by the workers and labels should be generated and pasted close to the buses to alert the personnel of the danger they are exposed to.

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