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Remediation of Old Substations for Arc Flash Hazard

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ABSTRACT

Arc Flash is much different from the conventional shock hazard in the sense that it doesn't involve direct contact of human beings with the live or energized part. The arcing energy involves high temperature of up to or beyond 20000K. This paper presents a case study of arc flash hazard analysis carried out in older industrial plant and the technological and work procedure changes that can be incorporated to reduce the incident energy level and thus provide a safer environment for the working personnels in plant.

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1. INTRODUCTION

Arc Flash Hazard even after extensive study remains an unexplored area in most of the substations in India as the switchgears used are almost 30 years old with protection system designed to address short-circuit fault isolation. Thus arc flash hazard levels for these existing substations is quite high allowing almost no work to be done in live panels even with PPEs of 20cal/cm2. However for maintenance activities in the vicinity of live areas and for online condition monitoring techniques like thermography the Switchgear Panels are to be opened and their thermal imaging is to be taken in their live condition thus making it unsafe for the operators. In order to mitigate this problem, certain changes can be made in these existing switchgears as well as in Protection settings to make them safer for human operations and also the cost involved can be justified with the savings in cost by avoiding failure and consequent damage.

There are several methods suggested till now to carry out the arc flash calculation [1]-[4]. However, IEEE method based on experimental results and empirical formulas derived therein are found to be most accurate

First step is to carry out arc flash hazard analysis of the existing switchgear so that the problem areas can be identified and improvements or changes can then be suggested as per feasibility.

2. ARC FLASH HAZARD ANALYSIS

In order to carry out the arc flash hazard analysis, first of all data collection is the single most important and cumbersome task which takes a lot of time and if maintained properly can lead to easy incorporation for future changes. In an old Industrial substation/plant, the arc flash analysis can be carried out in the following stepwise manner so as not to miss anything:

The whole plant/substation should be divided into sections or areas. Individual working personnel most familiar should be given areas to gather data for all equipments in that particular area so that no equipment is missed out. While carrying out this survey, the equipments should also be labeled by their voltage and source feed, if not already done. A spreadsheet should be made and following data should be captured in that.

a. Generator
   i. Rating (MVA)
   ii. Sub-transient reactance
   iii. Bus to which connected
b. Transformer
   i. Rating (MVA)
   ii. Voltage Ratio
   iii. Percentage impedance
   iv. Bus to and from
c. Transmission Line
   i. Length (km)
   ii. Type of Conductor
   iii. Impedance (Ω/km)
   iv. Number of lines in parallel
d. Motor
   i. Rating (kW)
   ii. Type of motor
   iii. Ratio of starting current to rated current
e. Cable
   i. Size of cable
   ii. Material
   iii. Make
   iv. Rating (A)
   v. Length of cable
   vi. Number of runs
   vii. Bus to and from
f. Relay
   i. Type (Electromechanical/Solid state/Numerical)
   ii. Setting range
   iii. Setting (PSM, TMS/Set current, time)
g. CT
   i. Ratio
   ii. Secondary rating
h. Breaker
   i. Breaking capacity
   ii. Trip units, if any
i. Bus
   i. Names
   ii. kV Level
   iii. Design Fault withstand levels
   iv. Conductor gaps
   v. Switchgear type (Box or Open)

The data captured above can be used to prepare an updated single line diagram incorporating the ratings of equipment and the relay settings. Also, various configurations of operation of Power system should be mentioned on the SLD (Single Line Diagram) indicating the status of breakers, transformers etc. during these configurations. Separate SLDs can be made for this purpose.

There should be a listing of jobs being carried out in plant at various times including any switching operations, maintenance jobs, testing etc.

The listing should also include the nature of job i.e. whether it is to be done online/offline. Most of the jobs to be carried out in a substation can be done in de-energized state thus making the job safe for the workers. For further insurance of safety for such kind of jobs, prior to carrying out the job, the de-energized state should be confirmed by a tested voltage detector. This will avoid human errors like working on the neighboring compartment, any breaker accidentally remaining closed etc. Also the voltage detector should be tested near any live equipment every time it is being used to ensure it does not give erroneous indication. Proper grounding should be provided not by insulation stick but by fixed clips to ensure the system is grounded while carrying out the job. The removal of grounding should be ensured before restoration of supply (to be incorporated in check sheet).

Thus, Jobs to be done in live state are very limited. Out of these, the remote operation and remote racking of breakers can further reduce the exposure level of workers. The remote operation can be implemented by making simple changes in the control circuit of the equipment while it is taken out for maintenance. Remote racking, while not always physically possible in existing plants, can always be considered a possibility and retrofitting feasibility should be checked. Such Jobs require bare minimum change to the existing equipment and are most economical. They should be identified from the list of jobs and changes should be planned in a phase wise manner during their scheduled outage.

Fig. 1. Remote Power Racking Unit

Only those jobs should be highlighted which cannot be done in de-energized condition. The fault levels at these job locations should be calculated by carrying out Short circuit study. It should be ascertained that the Buses/cables/Breakers/CT secondary are designed for withstanding these fault levels as in any old substation many loads are added later on or the buses are extended without paying much attention to the design withstand fault levels. Relay coordination for the existing relay settings should be confirmed before carrying arc flash analysis. Any adjustments in relay settings, if required, should be made at this point.

The arc fault current levels should be calculated at the identified job locations as per IEEE 1584. The time of operation as per the relay settings for the arc fault current should be determined.

The incident energy and flash protection boundary can then be calculated by the empirical equations given by IEEE 1584 and the areas with energy levels > 1.2 cal/cm2 are to be identified.

At this point, the identified locations with incident energy levels > 1.2 cal/cm2 should be checked for these points, if applicable, to bring down the energy levels:

1. While carrying out any switching actions there should be well documented procedures/ checksheets marking even the switch and compartment number to avoid human mistakes.
2. During maintenance of a breaker if any check on live bus bar is to be made to check pitting, it should be made by two-pronged shutter lifter made of insulator.
3. Only Trained Personnels should be allowed for such jobs in presence of a standby person to avoid errors. Personnels should be given live demo on spare on decommissioned equipment.
4. Provision of viewing window with better emissivity for jobs like thermography so that the panel compartment is not required to be opened
5. Provision of Maintenance bypass switch to incorporate an alternate set of relay settings for instantaneous operation of relay in the event of fault while working on the system. These settings should be normalized after the job is finished.
6. Retrofitting to arc resistant switchgears in specific problematic areas.
7. Use of Category III or IV multimeter.
8. If there is a load mixup of areas in MCCs, this should be rectified in any scheduled outage so that it does not cause heartburn.
9. Provision of fused incoming and change fuses of normal type with current limiting type (class RK1).
10. In earlier designs the LV motors are provided with only short-circuit (cleared by fuses) and thermal protection (cleared by contactor). While for faults involving two phases and single-phase ground, the fuse will take a lot of time for clearing the fault. Thus the cost vs benefit for providing additional relay protection on high rating motors for fast isolation should be carefully considered. For this, the LV

contactors breaking capacity in case of faults should be checked. Other Solutions - Temporary Reduced Settings, Arc Sensing Relays, Zone Selective Interlocking, Arc Containment Device and PPEs. The temporary reduced settings of relay requires specific capable trip systems and does not provide protection if the event does not occur during the planned activity. The provision of light sensors along with current input from CT and Zone selective interlocking can also be used for instantaneous tripping purpose for the arc fault. However for higher hazard risk category jobs even the 3-cycle time to be taken by breaker to clear the fault will not be acceptable. Thus in such cases, arc containment device can be used. The last line of defense can be PPE to be used while working. In market as of now even 40cal/cm2 suits are available. But these suits are very bulky and may lead to difficulty in carrying out the job. Thus, after reducing the energy levels as much as possible by other means as described above, the PPE should be chosen. After this, as per The National Electrical Code (NEC), Section 110.16, a Arc Flash Hazard Warning label should be placed on the equipment to warn the qualified persons of potential electric arc hazards. It should be placed so as to be clearly visible, should include the Hazard risk category, flash protection boundary and recommended PPEs required if work is to be done in normal working distance. Here for study a sample single line diagram is taken where the bolted fault levels and protective device ratings are calculated for different possible configurations for operating the Power System. Other Solutions - Temporary Reduced Settings, Arc Sensing Relays, Zone Selective Interlocking, Arc Containment Device and PPEs. The temporary reduced settings of relay requires specific capable trip systems and does not provide protection if the event does not occur during the planned activity. The provision of light sensors along with current input from CT and Zone selective interlocking can also be used for instantaneous tripping purpose for the arc fault.

However for higher hazard risk category jobs even the 3-cycle time to be taken by breaker to clear the fault will not be acceptable. Thus in such cases, arc containment device can be used. The last line of defense can be PPE to be used while working. In market as of now even 40cal/cm2 suits are available. But these suits are very bulky and may lead to difficulty in carrying out the job. Thus, after reducing the energy levels as much as possible by other means as described above, the PPE should be chosen. After this, as per The National Electrical Code (NEC), Section 110.16, a Arc Flash Hazard Warning label should be placed on the equipment to warn the qualified persons of potential electric arc hazards. It should be placed so as to be clearly visible, should include the Hazard risk category, flash protection boundary and recommended PPEs required if work is to be done in normal working distance. Here for study a sample single line diagram is taken where the bolted fault levels and protective device ratings are calculated for different possible configurations for operating the Power System.

3. SAMPLE SYSTEM FAULT CALCULATION

The Single Line diagram for the sample system is as shown below:

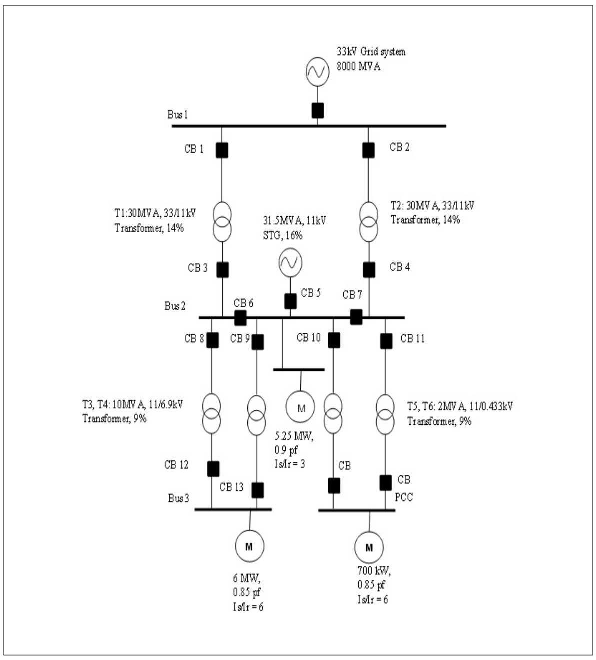

Fig. 2. ingle Line Diagram of a Sample system

The Sample system consists of a plant having Captive Power Generation of 31.5MVA in order to self-sustain the plant along with running it in parallel with the grid for improved reliability.

The Power from grid is being received by the plant at 33kV level and then is being step down to 11kV, 6.6kV and 415V for subsequent distribution to loads.

At each distribution level there are 2 transformers each individually capable of feeding the load. The extra capacity is provided for future usage.

Now short circuit study is carried out on the given system to calculate bolted fault current levels. Here, Different operating configurations and their impact on Bolted fault current and arc flash levels is considered. The different cases considered are:

Case 1: T1, T3, T5 in line

Case 2: T1, T3, T4, T5, T6 in line

Case 3: T1, T2, T3, T5 in line

Case 4: All Transformers in line

Thus bolted fault current levels of the buses are as given in Table I. Here Bus 1 is not considered as it is directly connected to the grid and any work on it will be done after disconnecting from the grid.

TABLE I. FAULT CURRENT WHEN SYSTEM RUNNING IN PARALLEL WITH GRID

Bus Name	Voltage level (kV)	Bolted Fault Current (kA)			
		Case 1	Case 2	Case 3	Case 4
Bus 2	11	16.87		22.47	
Bus 3	6.6	10.93	15.2	11.42	16.5
PCC	0.415	28.9	54.32	29.39	56.02

As can be seen the fault levels vary widely with different operating configurations and also with the rating of different equipment like transformer, generator chosen during system design. The least fault level of system is there when only one transformer is operated. But this will decrease the reliability of the system as this transformer failure can lead to complete loss of power. Further even with one transformer operation the fault current levels will change with system operation in parallel with grid or in isolated condition (as shown in Table II).

Case 5: Isolated + T3, T5 in line

Case 6: Isolated + All Transformers in line

TABLE II. FAULT CURRENT WHEN SYSTEM RUNNING IN ISOLATED CONDITION

Bus Name	Voltage level (kV)	Bolted Fault Current (kA)	
		Case 5	Case 6
Bus 2	11	11.25	
Bus 3	6.6	6.4	9.55
PCC	0.415	28.012	51.19

Thus, a compromise has to be reached between reliability and fault level of system. The design of the system as well as the configuration in which it is operated has a major impact on the arc flash levels. The study should be carried out for arc flash current levels and energies keeping all the scenarios of system operation in mind so as to ascertain the best operating scenario.

4. PROTECTIVE DEVICE COORDINATION

Relays provided at different levels, their settings and characteristics data for the SLD given is determined based on the load data, fault levels, relay coordination [6] etc. The coordination curves are as given below. As of now, arc flash protection is not taken into consideration and calculations are done only for bolted fault current levels.

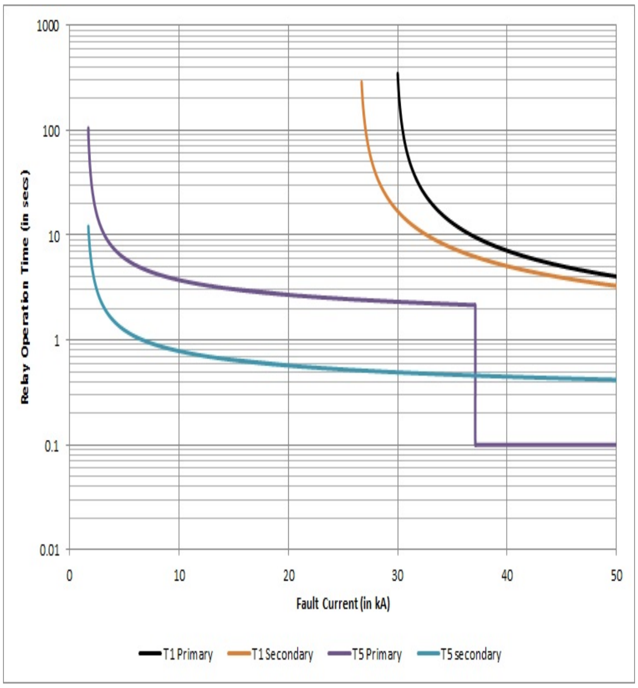

Fig. 1. Relay Coordination of 415V system before arc flash calculations are taken into consideration

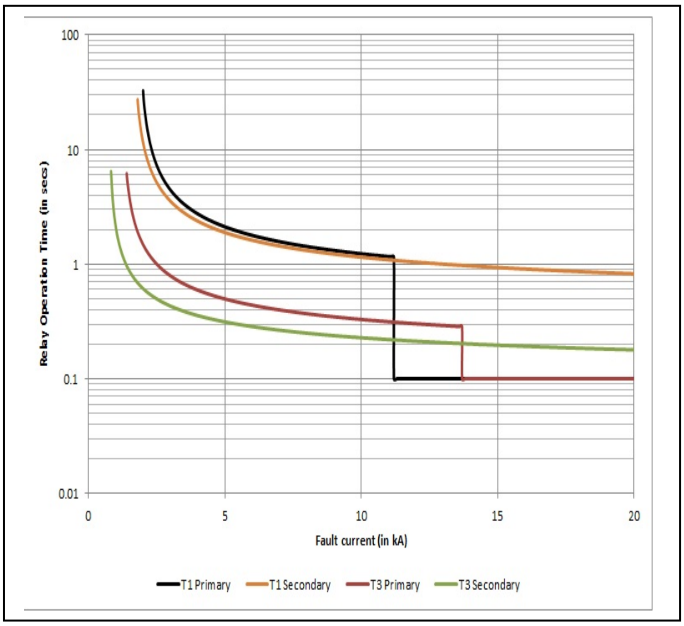

Fig. 2. Relay Coordination of 6.6kV system before arc flash calculations are taken into consideration

During the relay selection and coordination when arc flash current is not taken into account, the two most important features to be kept in mind are that the selective coordination should be strictly followed i.e. the breaker closest to the fault should operate first and if it fails to operate, only then the upstream breaker should operate and in the event of starting of highest rating motor while other connected loads are running, the relay should have a time delay greater than the starting time of the machine so as to avoid erroneous operation of the protection system when there is no fault.

5. ARC FLASH CALCULATION

Many methods for Arc fault Hazard level calculation have been given till now. Ralph Lee's method is one of the first methods but it gives conservative results and is only referred for voltage levels beyond 15kV for which the tests by IEEE were not carried out. The IEEE 1584 method till now is the most accurate method as it has been found out on the basis of regression analysis of the experimental data obtained by carrying out the test.

As per IEEE 1584 [1], the empirical equations for arc flash levels are as given below:

a. Arc Fault Current and Clearing time

For PCC (< 1kV system),

Arc Fault Current,

$$I_a = 10^{(K + 0.662 \log(I_{bf}) + 0.0966V + 0.000526G + 0.5588V \log(I_{bf}) - 0.00304G \log(I_{bf}))}$$

Where, K = -0.153 for open configuration and -0.097 for box configuration

V = system voltage in kV,

G = conductor gap in mm

I_{bf} = Bolted Fault Current

I_a = Arc fault Current

For Voltages >1kV and < 15kV,

$$I_a = 10^{(0.00402 + 0.983 \log(I_{bf}))}$$

The fault clearing time for I_a and 85% of I_a can be checked from the relay operation curve.

From this calculated arc fault current and the fault clearing time, the incident energy at a distance of 610mm from the source of arc is ca lculated as given below:

b. Normalized Incident Energy and Incident energy at working distance

Normalized Energy,

En = 10 (K1 + K2 + 1.081 log Ia + 0.0011G)

Where,

K1 = -0.792 for open configuration and
-0.555 for box configuration,

K2 = 0 for ungrounded and high resistance grounding and
-0.113, grounded system

E_n is in J/cm^2 (5 J/cm^2 = 1.2 cal/cm^2)

Incident energy, $E = 4.184 C_f E_n (t/0.2)(610^x/D^x)$

Where, C_f = calculation factor
= 1, > 1kV
= 1.5, <= 1kV

x = 1.473, switchgear (<1kV)
= 0.973, switchgear (>5 – 15 kV)
D = working distance in mm
En = normalized incident energy

For V> 15kV, Ralph Lee's method [2] is used for Incident energy calculation

$E = 2.142 \text{ X } 10^6 \, V \, I_{bf} (t/D^2)$

The arc flash current, its clearing time, incident energy released at working distance are provided in the Table III, IV and V for different buses at various bolted fault current levels for configurations considered above.

TABLE III. INITIAL ARC FLASH LEVELS AS PER IEEE 1584 (BUS 2)

Bus No.	Voltage (kV)	Case	Bolted Fault Current (kA)	Arc Fault Current (kA) 100% and 85%	Time of clearing arc fault current (sec)	Incident Energy released at working distance (cal/cm2)
Bus 2	11	1	16.87	16.23	0.1	2.184
				13.79	0.1	1.832
		2	16.87	16.23	0.1	2.184
				13.79	0.1	1.832
		3	22.47	21.51	0.1	2.962
				18.28	0.1	2.484
		4	22.47	21.51	0.1	2.962
				18.28	0.1	2.484
		5	11.25	10.9	0.1	1.42
				9.26	0.1	1.191
		6	11.25	10.9	0.1	1.42
				9.26	0.1	1.191

TABLE IV. INITIAL ARC FLASH LEVELS AS PER IEEE 1584 (BUS 3)

Bus No.	Voltage (kV)	Case	Bolted Fault Current (kA)	Arc Fault Current (kA) 100% and 85%	Time of clearing arc fault current (sec)	Incident Energy released at working distance (cal/cm2)
Bus 3	6.6	1	10.93	10.59	0.2232	2.72178
				9	0.2382	2.4367
		2	15.2	14.65	0.1982	3.4312
				12.45	0.21	3.0498
		3	11.42	11.06	0.2196	2.8056
				9.4	0.234	2.5079
		4	16.5	15.88	0.1928	3.6419
				13.5	0.204	3.2326
		5	6.4	6.26	0.2801	1.9341
				5.32	0.3038	1.7597
		6	9.55	9.28	0.2353	2.4859
				7.88	0.252	2.2334

TABLE V. INITIAL ARC FLASH LEVELS AS PER IEEE 1584 (PCC)

Bus No.	Voltage (kV)	Case	Bolted Fault Current (kA)	Arc Fault Current (kA) 100% and 85%	Time of clearing arc fault current (sec)	Incident Energy released at working distance (cal/cm2)
PCC	0.415	1	28.9	14.16	0.6608	19.9886
				12.04	0.7137	18.1105
		2	54.32	23.73	0.5345	28.2471
				20.17	0.5689	25.2211
		3	29.39	14.36	0.6567	20.1637
				12.2	0.7088	18.2563
		4	56.02	24.33	0.5295	28.7558
				20.68	0.5633	25.6626
		5	28.012	13.8	0.6686	19.6742
				11.73	0.7226	17.8383
		6	51.19	22.604	0.5444	27.3
				19.21	0.58	24.3988

From the above tables, it can be clearly seen that the most favorable scheme of operation under normal condition is Case 1 with one transformer only in operation. When work is to be done on energized equipment, the best mode of operation is Case 5 i.e. in isolated condition with only one transformer in operation to feed each bus.

Any changes in the setting of the relay to bring down the clearing time so as to lower the incident energy in older plants with limited range of settings in the existing electromechanical relays results in Relay coordination disturbance and may lead to operation of the relay even under through fault conditions and isolation of even normal areas.

Under these limitations two possible actions that can be taken are:

Zone Selective Interlocking

Zone Selective Interlocking (ZSI) can be incorporated in such a case so that if the breaker nearest to the fault senses it will give locking command to the upstream breaker and will clear the fault without any intentional time delay irrespective of the setting of the relay.

Temporary Reduced Setting

Another feasible solution for this is by providing maintenance bypass switch which will provide a different set of relay settings during any maintenance activity thus giving instantaneous clearance of arc fault or by providing unit differential protection on the bus, the fault current levels and thus the incident energy can be reduced substantially. The levels thus reduced are given in Table VI.

TABLE VI. FINAL ARC FLASH LEVELS AS PER IEEE 1584 BY LOWERING CLEARING TIME

Bus No.	Voltage (kV)	Bolted Fault Current (kA)	Arc Fault Current (kA)	Time of clearing arc fault current (sec)	Incident Energy released at working distance (cal/cm2)
Bus 2	11	16.87	16.2283	0.1	2.184
Bus 3	6.6	10.93	10.5921	0.1	1.22
PCC	0.415	28.9	14.1615	0.1	3.025

The Flash Protection Boundary is defined as an approach limit at a distance from live parts that are uninsulated or exposed within which a person could receive a second degree burn (IEEE 1584[1]). It can be calculates as.

c. Flash Protection Boundary

$D_B = [4.184 C_f E_n (t/0.2) (610^x/E_B)]^{1/x}$

Or by Lee's method,

$D_B = [2.142 \text{ X } 10^6 \text{ V } I_{bf} (t/E_B)]^{1/2}$

Where,

E_B = 5 J/cm^2 for bare skin (second degree burns, curable)
= 33.33 J/cm^2 for PPE of 8 cal/cm^2

Thus, flash protection boundary i.e. safe working distance for bare skin and with PPE of 8 cal/cm^2 [5] before and after remediation is shown in Table VII and VIII.

TABLE VII. FLASH PROTECTION BOUNDARY BEFORE REMEDIATION

Bus No.	Voltage (kV)	Flash Protection Boundary (m) IEEE 1584	
		1.2 cal/cm^2 (bare skin)	8 cal/cm^2 (PPE)
Bus 2	11	1.68	0.24
Bus 3	6.6	2.1	0.3
PCC	0.415	3.4	1.065

TABLE VIII. FLASH PROTECTION BOUNDARY AFTER REMEDIATION

Bus No.	Voltage (kV)	Flash Protection Boundary (m) IEEE 1584	
		1.2 cal/cm^2 (bare skin)	8 cal/cm^2 (PPE)
Bus 2	11	1.68	0.24
Bus 3	6.6	0.925	0.132
PCC	0.415	1.071	0.337

As can be seen from above the approach distances and incident energies reduced considerably for the 415V PCC system and 6.6kV Bus. With PPEs of 8 cal/cm2, the work can be safely done without any harm to the operators.

Arc Containment Device [6]

Another solution that can be used is the arc containment device [6] which is essentially an enclosure containing electrodes. With the help of trigerring through light sensors and CT input the plasma gun can be used to divert the arc from the switchgear to this device with impedance lower than the arcing impedance. Thus arc current starts passing through this chamber and the interruption of arc takes place in 7-8ms as compared to almost 100ms taken by the breaker. This leads to drastic reduction of the arc energy and safety of workers. The calculations are shown in Table IX with a clearing time of 10ms.

TABLE IX. FLASH PROTECTION BOUNDARY AFTER REMEDIATION WITH THE HELP OF ARC CONTAINMENT DEVICE

Bus No.	Voltage (kV)	Flash Protection Boundary (m) IEEE 1584 1.2 cal/cm^2 (bare skin)
Bus 2	11	0.158
Bus 3	6.6	0.087
PCC	0.415	0.263

But prior to using the arc containment device, its effect on the BIL of the system or any other harmful effects during normal operation of the Power system should be considered. Care should be taken so that this unit does not operate under normal switching operations. For this test should be carried out after commissioning and before taking into line. Also, there should be provision of checking the condition of electrodes and replacement if required during routine maintenance or after failure.

7. CONCLUSION

Safety of working personnel is paramount while carrying out any job on electrical equipment and any mistake could lead to damage to both personnel working in the vicinity and equipment. To avoid such occurrences, As much as possible, the maintenance work on any electrical system should be carried out after de-energizing the equipment to be taken for maintenance and proper work procedures and checks should be put into practice prior to starting the job. However, if it is impossible to avoid working on live panels like in case of Thermography etc., It has been found from the above calculations that by minor changes in the Protection logic of the existing system the safety of the working personnel can be ensured.

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