# Arc Flash Incident Assessment and Mitigation: A Case Study of Fatal Accident due to 6.6kV Bus Coupler Switch Gear Flashover at Central Waste Management System (CWMS) in PFBR

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**Abstract:** ***Electricity is a vital part of our modern world. Human cannot even think about a single day without electricity in life. The number of occupational electrical accidents in Indian industries declined over the last decade, but technician, worker injuries and fatalities still occurs among the country. Contemporary measures to increase electrical safety are not effective enough. In order to condense the number of electrical accidents, there is a necessity for more information about electrical accident risks at the operative level. This review presents case study of electrical fatalities due to electrical flashover in 6.6kV Bus Coupler Switch Gear at Central Waste Management System (CWMS) in Prototype Fast Breeder Reactor (PFBR) in India, its assessment and mitigation techniques to reduce similar electrical accidents.***

**Keywords:** Electrical Hazard, Arc Flashover, Residual Charge, Partial Discharge, PPE

## 1. Introduction

Arc flash is a non-contact short circuit between an energized conductor such as a busbar or cable with another conductor or an earthed surface. Put simply, arc flash is precipitated by insulation breakdown and very often, the insulation in question on low/medium voltage systems is air.

A cause of insulation breakdown is commonly by human intervention when performing, either deliberately or inadvertently, unjustified live working activities. This can be fleeting through the dropping of un-insulated tools and cable armours or the use of damaged instruments. It can also be caused by neglect or moisture ingress.

Once initiated, the insulating medium will be ionized providing a low impedance path. The resultant fault current creates a conducting plasma fireball with arc temperatures that can reach upwards of 20,000 degrees centigrade at its center which will vaporize all known materials close to the arc immediately. The thermal energy emitted may ignite materials at a distance from the arc which may include a worker's clothing and/or cause life changing burns.

The significance of arc flash in electrical safety cannot be overstated. It poses a serious risk to workers and equipment in environments where electrical systems are present. An arc flash can generate temperatures up to 35,000°F (about 19,427°C), which is several times hotter than the surface of the sun. The energy released in the event of an arc flash can cause severe burns, blast injuries, and other life-threatening conditions.

Common causes of arc flash incidents include a variety of factors. An arc fault, which occurs due to electricity improperly discharging between conductors, is a significant cause of arc flashes. Arc faults can lead to dangerous situations and understanding them is crucial for improving safety and preventing electrical accidents. Some of the most common causes of arc flash are:

- Equipment Failure
- Human Error
- Environmental Factors

It's important to note that while these are common causes, arc flash incidents are complex and may involve a combination of these factors. Preventing arc flashes in an organization requires a comprehensive approach that includes regular equipment maintenance, proper training, use of appropriate tools, and adherence to safety standards and procedures.

## 2. Literature Survey

Arc flash is one of the most severe hazards in medium-voltage (MV) electrical systems, resulting from phase-to-phase or phase-to-ground insulation failures. The phenomenon produces high thermal energy, intense light, pressure waves, and molten metal, posing significant risks to both personnel and equipment. According to IEEE 1584 [1], incident energies in MV switchgear can exceed 40cal/cm² within a few cycles, making arc flash assessment a critical element of power system safety.

The majority of arc flash incidents occur in switchgear operating between 3.3 kV and 11 kV. Studies by Wilkins et al. [2] and Doan [3] highlight that MV switchgear is particularly vulnerable due to aging insulation, high fault currents, and inadequate maintenance. Among MV components, **circuit breakers and bus couplers** are frequently reported as points of failure, often triggered by insulation degradation, tracking, and operational stresses. Research also indicates that equipment condition plays a larger role in arc initiation at MV levels compared to low-voltage systems. Several international standards provide frameworks for arc flash hazard analysis:

- **IEEE 1584-2018** – Empirical formulas for incident energy and arc flash boundaries considering electrode orientation, enclosure size, and grounding type [1].
- **NFPA 70E** – Prescribes safe working distances, PPE categories, and work practices for energized systems [4].
- **OSHA Regulations** – Mandates arc flash hazard labeling and protective measures in workplaces [5].

Comparative studies suggest that IEEE 1584 offers more reliable predictions for MV systems than NFPA 70E due to its experimental basis and updated parameters for higher voltages [6].

The review of existing literature highlights that arc flash in 6.6 kV breakers is a critical safety concern due to the high incident energy involved. While IEEE 1584-based methods and modern protection technologies provide effective means of assessment and mitigation, case-specific studies on arc flash incidents in **6.6 kV bus coupler breakers** remain scarce. This gap underscores the importance of the present work, which aims to assess an actual incident and propose targeted mitigation strategies for medium-voltage switchgear.

## 3. Methodology

In this paper the case event was first analyzed with help of Fault Tree Analysis (FTA) diagram shown in Fig. 1 which would facilitate to understand the case and subsequent risk assessment and mitigation.

Risk assessment involving Arc Flashover is carried out through 4P approach. While carrying out a risk assessment, as a minimum we must:

a) Identify what could cause injury (hazards)
b) Decide how likely it is that someone could be harmed and how seriously (the risk)
c) Take action to eliminate the hazard, or if this isn't possible, control the risk:

The cycle matrix diagram shown in Fig. 2 illustrates how the important first step of **Predict** is used to calculate the severity of the arc hazard. This is followed by **Prevent** in that we apply the principles of prevention and order the risk control measures in a hierarchy. The next step is **Process**, policies and procedures where we apply the building blocks of safe procedures, safe places and safe people. The final step is **Protect** which looks at providing PPE as a last resort which, if the previous three steps have been correctly applied, will deal with residual risk only and be more lightweight optimum solutions.

## 4. Narration of the Case

Yearly Preventive Maintenance (YPM) of Class-IV 6.6kV bus coupler switch gear (Vacuum Circuit Breaker) was being taken up by Electrical Maintenance Unit (EMU). One departmental supervisor, one departmental technician and one contract helper were assigned for carrying out said maintenance job.

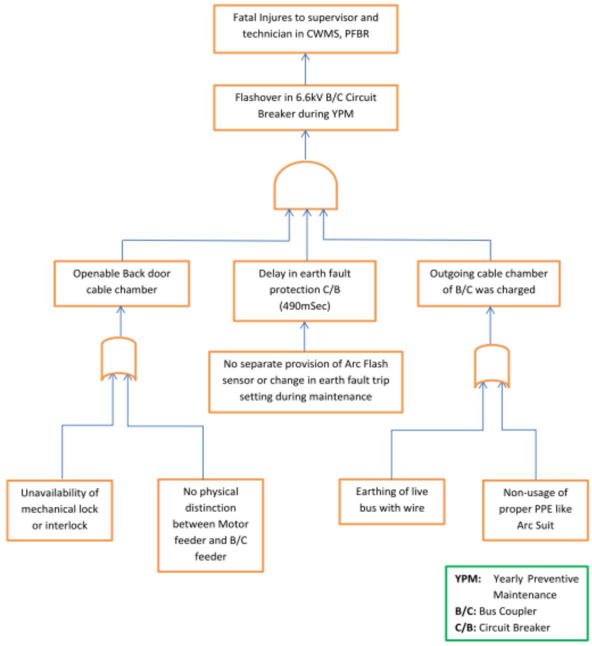


**Figure 1:** Fault Tree Analysis of the Event


**Figure 2:** 4P Cycle Matrix

On the day of the accident (September 28, 2024), VCB of the bus coupler was switched off and racked out by operator (from operation section) at 11:00 hrs and after clearance of permit from Shift Charge Engineer, maintenance work on VCB of the bus coupler was initiated before lunch. After lunch break, Supervisor and helper proceeded to the job location together and resumed maintenance activities on VCB panel before technician could reach the location.

At around 14:30 hrs, the flashover took place and witnesses found said supervisor and helper running on the road, with their clothes burnt out. Later, few other employees arrived at the scene and helped both of them in the Ambulance. Both the injured personnel were rushed to hospital for further treatment. Unfortunately, during subsequent treatment, said helper succumbed to his injuries.

**Causes of Accident**

**a) Flawed Work Permit System- Combined Permit & Deficiency Report:**

The work permit was issued from the MCR for YPM checks on Bus Coupler (HVBwm51-100A and 100B located in Panel 7 of Class-IV Switchgear) on 27.09.2024 and was valid till 30.09.2024. The deficiency report/work permit


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failed to identify the activity as hazardous, and in requirement of industrial safety instructions from the Safety Section. The DR mentioned isolation of only Vacuum Circuit Breaker (VCB), which meant that the bus bars will be in energized condition. However, there was no specification of hazards or any specific instructions indicating the do's and don'ts of working with 6.6 kV bus bar panel. MCR also failed to highlight the hazards of accessing Panel No. 7 which was different from the nearby panels.

**b) Common Checklists for bus coupler maintenance & motor feeder maintenance:**

In VCBs of motor feeder, cable chamber is housing outgoing power cables with support bushings which becomes dead once VCB is isolated by racking out. However, in VCB of Bus Coupler, rear chamber (which is the bus chamber) is housing bus bars with support bushings which will remain energised even if breaker is isolated by racking out. Section G (Cable Chamber Check) of said checklist is not applicable for VCB of Bus Coupler, however, this was not brought out clearly and specifically in the procedure.

**c) Lack of clarity in Job Description & Pre-job briefing:**

Though the maintenance section was aware of the fact that the bus coupler was live and the particular panel did not require cleaning of the back chamber, the same was not explicitly communicated to the Supervisor.

**d) Absence of Physical Interlock:**

No mechanical lock or interlock was present to prevent opening the rear panel of the bus coupler chamber when buses are in energized condition.

**e) Use of small wire for discharge of residual charges:**

Before cleaning of bus bars, it is a usual practice to discharge the static charge, if any. Based on the evidence available (burnt insulated wire was found at the location), maintenance staff might have tried to discharge the terminal with a wire. Since the bus bars were live, that might have caused the flash over.

**f) No separate demarcation of bus coupler breaker:**

From the rear side, all the panels (for bus coupler as well as motor feeder) look similar. There was no demarcation of any type between two types of VCBs. Maintenance staff might have thought of bus coupler breaker similar as motor feeder breaker.

**g) Absence of Arc flash hazard Mitigation Strategies:**

Arc flash hazard is an inherent hazard associated with electric power system. To reduce the risks of arc flash injures to occupational workers while working on electrical systems, a number of different strategies such as optical arc flash detection relays, reduced trip stetting during maintenance activities, etc. are used. For the 6.6kV power system in the plant, only the time delayed overcurrent/earth fault (51/51N) protection function was enabled in the protection relay. No instantaneous overcurrent/earth fault (50/50N) protection function was used. On the day of the event, the relay tripped with a time delay of 490ms, rather than instantaneously. A properly set instantaneous overcurrent/earth fault protection could have tripped almost instantaneously (<50ms), considerably reducing the incident energy (roughly by 1/10th) and thereby the severity of the arc flash burns.

**h) Non-usage of Arc Suit:**

Involved maintenance staff did not use Arc Flash suit while working on VCB. Also, there were no instructions on use of Arc Flash Suit in the Checklist/Procedure/permit for the said job.

## 5. Risk Assessment and Mitigation through 4P approach

### 5.1 Prediction

The first step in the 4P approach is to predict the severity of an arc flash. By predicting the severity of the thermal effects of an arc flash, a measure of incident energy levels can be obtained at a specific working distance from a prospective arc source. This is usually measured in joules/$cm^2$ and is also expressed in calories/$cm^2$. The figure of 5.0J/$cm^2$ (1.2cal/$cm^2$) is the level at which there is a 50% chance of the onset of a partial thickness or minor second-degree burn. This figure is important as it is used to determine the attenuation of heat energy on the skin afforded by protection systems and also to determine the arc flash protection boundary, which is distance from a prospective arc source at which the incident energy is calculated to be 5.0J/$cm^2$ (1.2cal/$cm^2$).

Predicting the severity of the arc hazard has been made more reliable in recent years through the publication of IEEE 1584 Guide for Performing Arc-Flash Hazard Calculations 2018. It is an auditable standard and widely accepted in the global electrical engineering community. 200 technical experts were involved in the development of the guide over many years and were based on over 1860 tests performed at different voltage levels in high current laboratories. To quote from the scope of the guide: "The purpose of the guide is to enable qualified person(s) to analyze power systems for the purpose of calculating the incident energy to which employees could be exposed during operations and maintenance work". It gives no recommendations for PPE. IEEE 1584:2018 is therefore the flagship standard for determining the incident energy (thermal hazard) from an arc at three phase voltages in the range of 208 volts to 15,000 volts AC.

### 5.2 Prevention and Minimization

Prevention must be the fundamental safety principle for the management of arc flash hazard. What this means is that the Duty Holder must always seek to design out, eliminate or remove the hazard at its source. This leads to the conclusion that most electrical tasks must be carried out with the equipment made dead, isolated and appropriately earthed. This section is dedicated to prevention starting with the elimination of live working but then going on to describe various practical solutions to help the reader to understand methods and technologies that are available. The following risk control measures (Table 1) gives more detail about specific risk reduction measures.

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**Table 1:** Risk Control Measures

| Risk Reduction Measures | Description | Brief Overview |
|---|---|---|
| Static Charge Discharge | Elimination of live working | It is the most effective risk reduction method. Proper earthing of the bus bar should be done to discharge static charge, if any, before working on the circuit breaker for maintenance purpose. |
| Automatic disconnection of supply (ADS) | Improved protection schemes | During maintenance, trip setting of earth fault relay should be temporarily changed to instantaneous. This can also be achieved by retrofitting instantaneous relays to override normal protection devices. |
| | Arc detection | Instantaneous tripping using an optical sensor to detect UV light emitted from an arc flash together with rate of increase in fault current will reduce the flashover hazard to a greater extent. |
| Equipment Design | Separation between power and control compartment of switchgear assemblies | Appropriate physical separation between low voltage control compartment and medium voltage power compartment can reduce likelihood. |
| | Proper Demarcation | Proper demarcation (colour coding, flag, signs etc.) should be done for motor feeder circuit breaker and bus coupler circuit breaker as both type of breakers look similar from rear side. |
| | Improved racking design | Breaker should be designed in such a way that live compartment at rear side should have been provided with physical lock or interlock arrangement. |
| Operational measures | Holistic approach to system design, installation and maintenance | Minimizing the risk of arcing requires whole life care involving distribution philosophy, system design, commissioning, maintenance, auditing and operation. Needs clarity of policies, leadership and control. |
| | Pre-job briefing | Pre-job briefing should be attended by the involved persons prior to taking up the activity. Such briefing should clearly explain Do's and Don'ts which will effectively help in preventing accidents. |
| | Training and Qualification | Organization should have proper electrical authorization and safety training program for its O&M personnel. An effective system of training and re-training (along with an assessment) of the electricians should be carried out focusing on ensuring that all jobs are carried out with increased responsibility and accountability. |
| | Nonintrusive diagnostics | Partial discharge, infra-red testing and gas in oil analysis can give warning of impending failure. Visual inspection by experienced competent person by carrying high voltage live potential indicator for checking equipment and apparatus dead. |

### 5.3 Process, Policies and Procedures

An organization must take full control of all tasks and activities related to electrical safety by embedding them within formal policies and procedures. At the very least, a written policy should be established, demonstrating senior leadership's commitment to electrical safety. Such a policy should form the foundation of safety rules, which provide effective control for electrical workers. These rules serve two purposes: first, to prohibit high-risk activities altogether and second, to regulate all other work so it can be carried out safely and should incorporate the following controls as a minimum:

a) Implementation of a comprehensive permit system to control access.
b) Restriction of access to live switchgear to those workers who are specifically authorized only.
c) Restriction of circumstances in which access to live switchgear may be granted.
d) Requirements for risk assessments before access to live equipment.
e) Specify tasks or interactions that are prohibited.

The following diagram (Fig. 3) may act as a checklist in respect of a dynamic risk assessment which can be incorporated into rules and procedures. By identifying hazards associated with live working, the checklist helps determine both the likelihood of harm and the potential severity of injuries. It highlights factors that must be evaluated to understand and minimize risks effectively.

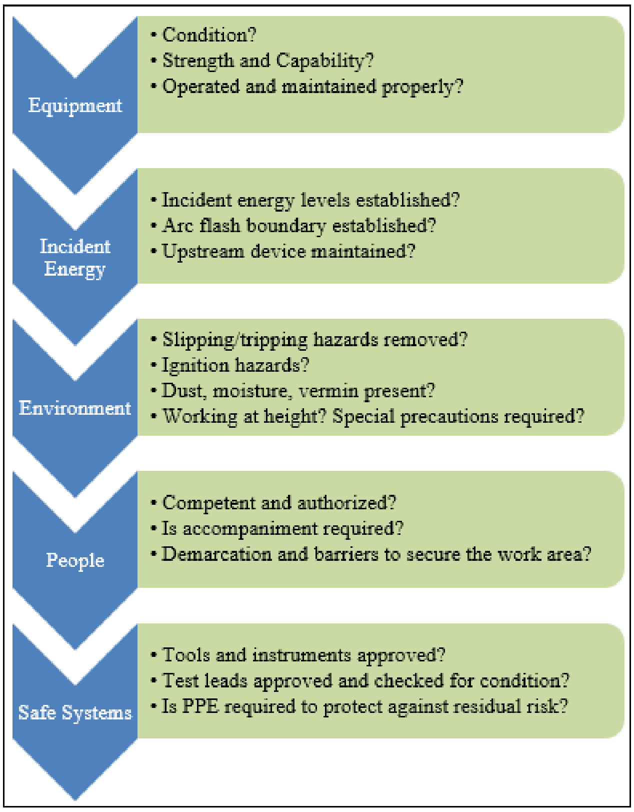


**Figure 3:** Checklist for dynamic risk assessment

### 5.4 Protection through PPE

When risks cannot be fully avoided or controlled through preventive measures, and a residual risk of injury remains, mitigation becomes necessary to protect workers. Assessing the need and suitability of mitigation techniques must be a core part of any risk assessment. Personal Protective Equipment (PPE) is considered the last line of defense—it cannot prevent accidents, but when used correctly, it has been proven to reduce the severity of injuries.

The analysis of risks which cannot be avoided by other means will begin with a quantitative assessment based on incident energy as outlined in the prediction step. This data can then be used to determine the protection level of the PPE which has to be greater than the predicted level of incident energy.

Before choosing PPE, we need to assess whether the PPE that we intend to use will satisfy the following requirements:

a) PPE must comply with country provisions on design and manufacture with respect to safety and health. For instance, in the UK and Europe all PPE must:
   - Be appropriate for the risks involved, without it leading to any increased risk.
   - Correspond to existing conditions at the work place.
   - Take account of ergonomic requirements and the worker's state of health.
   - Fit the wearer correctly after any necessary adjustment.

b) Where the presence of more than one risk makes it necessary for a worker to wear simultaneously more than one item of PPE, such equipment must be compatible and continue to be effective against the risk or risks in question.

The following diagram (Fig. 4) outlines the PPE analysis and assessment process:

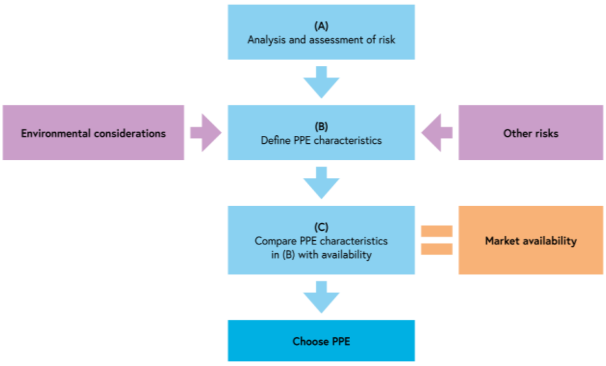


**Figure 4:** PPE analysis and assessment process

## 6. Conclusion

Arc flash is a serious hazard that has the potential to cause injury and death, but also catastrophic damage to valuable equipment and loss of critical supplies. A risk-based approach using the 4P model will ensure that elimination is always given priority, in tandem with sound engineering practices. PPE will always be the last line of defense. In this way, not only will workers be protected, but essential supplies will be maintained.

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