MINING ELECTRICAL AND MINING MECHANICAL ENGINEERING SOCIETY.
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NEWCASTLE BRANCH **ABN 13 772 583 769**

Postal Address: P.O Box 45, BOOLAROO. NSW. 2284
Hon. Secretary: Albert Weeks. Phone / Fax : (02) 4958 6827 Email: sysapprovals@hotmail.com
Hon. President: Ron Rennex.

CODE OF PRACTICE FOR THE CONTROL OF FAULT ARCS IN FLAMEPROOF ENCLOSURES USED IN UNDERGROUND COAL MINES

Compiled through MEMMES by representatives from:
The Coal Mining industry,
Manufacturers,
Regulatory and Testing Authorities.
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Appendix A

Management of High Energy Systems

By:
Dr. Alan Broadfoot B.E.(Hons), M.E., Ph.D., M.I.E.E.E., F.I.E.Aust.

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CODE OF PRACTICE FOR THE CONTROL OF FAULT ARCS IN FLAMEPROOF ENCLOSURES USED IN UNDERGROUND COAL MINES

1. FOREWORD

The purpose of this Recommended code of practice is to facilitate the safe, efficient and productive use of electrical explosion protected apparatus and cables operating at or above 3300 volts, in underground coal mine hazardous areas. The use of this document will enhance the management of safety risks and production risks at coal mines through good and safe electrical engineering practice.

The use of this document will contribute significantly to

- Prevention of electric shock and burns,
- Prevention of electrical arcing and surface temperatures that have sufficient energy to ignite gas and/or dust,
- Prevention of fires caused by the malfunction of electrical equipment, and
- Increased productivity.

Any electrical distribution and utilisation system should be specified, designed, installed, commissioned, operated, maintained (including servicing and repairs) and disposed of (life cycle), in a manner that manages the safety risks and production risks at the mine. This can be done through:

- Equipment that is fit for purpose throughout the life cycle,
- People who are competent in the relevant stage of the life cycle,
- Safe working procedures throughout the life cycle,
- Appropriate competent supervision throughout the life cycle,
- Managing the work environment throughout the life cycle,

All of this should be done within a management system framework with risk assessment and risk control as a key element. There are a number of fundamental risk controls associated with using electricity in hazardous areas; these risk controls can take on particular significance where the utilisation voltages are at, or above 3300 volts, these risk controls should form the basis of standards of engineering practice. The fundamental risk controls are:

- Fit for purpose electrical explosion protected apparatus,
- Fit for purpose cables for hazardous areas in a mining environment,
- Fit for purpose electrical protection.
- Fit for purpose earthing systems
- Fit for purpose lightning protection
- Fit for purpose automation (this allows the removal of people away from the hazard).
- Isolation and electrical testing procedures.
- Removal/restoration of power procedures.

- Proper classification of hazardous areas.
- Correct first aid treatment for persons who receive an electric shock and burns.

This recommended code of practice covers many of these particular aspects, but also takes a holistic approach to the electrical system and recognises that many of the risk controls interact and that each of the life cycle stages interacts. It is up to the user of this document to make judgements and decisions with all of this in mind.

2. INTRODUCTION

Much of this document has been drawn from a paper by Dr Alan Broadfoot of Ampcontrol, the work of Mr Rob Robson of Dynamic Electrical and research work conducted by SIMTARS. Dr Broadfoot's paper is reproduced in Appendix A.

There has been a steady increase in demand for energy in underground coal mines since mechanisation. This has been a natural outcome of increased demands on coal supply as the world's population increases and industrialises.

The initial underground utilisation voltages were between 32V and 415V. These have progressively increased through 1kV to 3.3kV while distribution voltages have increased from initially 2.2kv through 6.6kV to the present Industry Standard of 11kV. Overseas 22kV is already being used and presently in Australia investigations are under way for face voltages of 11kV and distribution voltages of 33kv.

The steady increase in voltage results from the need to increase the power supply to machines whilst keeping distribution cables to manageable sizes. Ultimately however, it is the quality of the power supply in terms of its energy rating rather than its voltage level that determines on-load voltage regulation at the point of utilisation and the resulting productivity levels.

Higher voltages reduce transmission losses and therefore improve the efficiency of power systems. However, it is the load to fault level ratio at the point of utilisation that determines machine productivity by maintaining the terminal voltage of motors at a value close to nominal.

However, the ever increasing demands on supply is reducing the safety margins on equipment and work practices as required fault levels to maintain efficient operation of machinery approach the limits of the equipment rating. Also, the risk associated with the higher energy levels are increasing placing more urgency on the development of quality standards of engineering practice and risk management of high-energy systems.

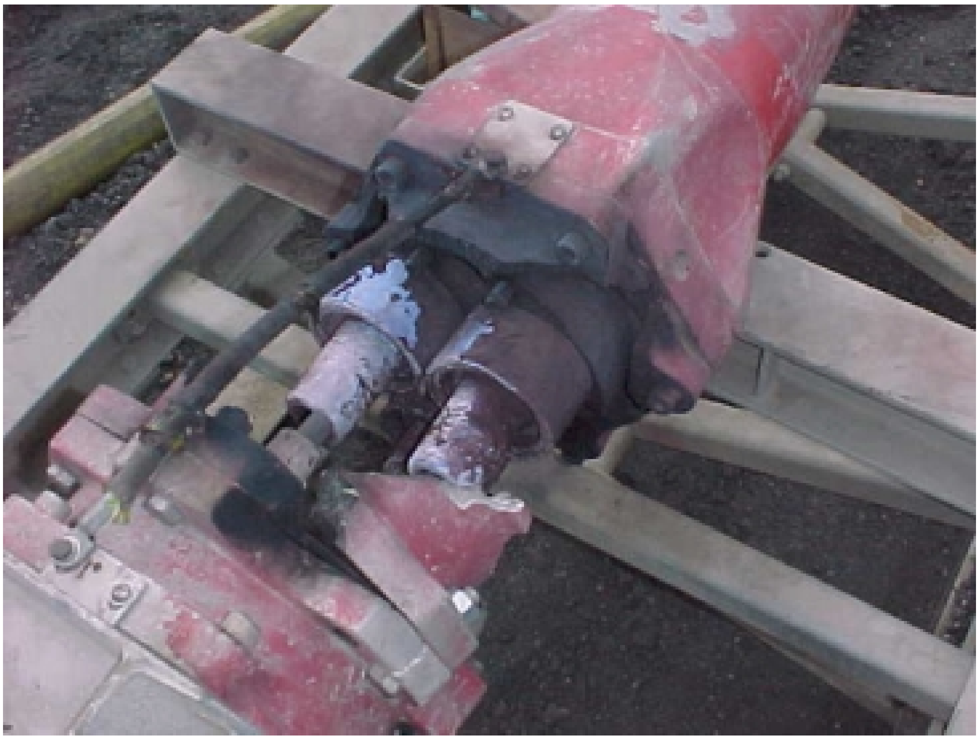
3. LEGISLATION

Whether through duty of care, or specific legislation there is a requirement for mine operators to consider the impact of internal arcing due to an electrical fault within a flameproof (Ex d) enclosure irrespective of the voltage source.

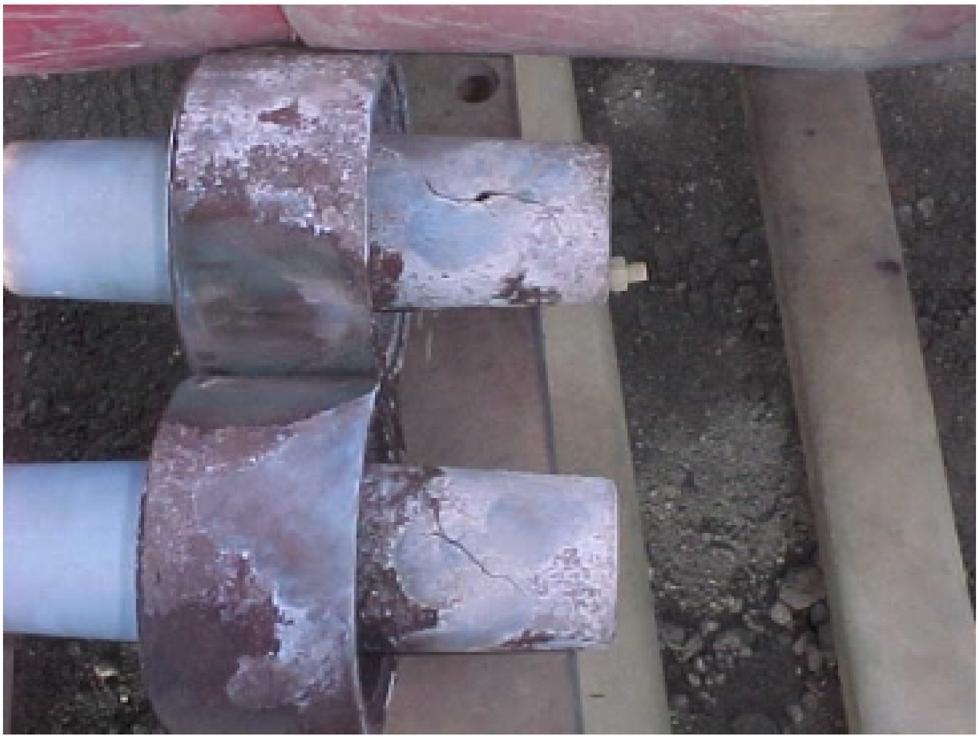
4. THE PROBLEM

Probably the most catastrophic event that can occur in any electrical enclosure is an arcing fault, particularly phase to phase arcs. Photographs 1 & 2 show the results of an arcing fault inside an 11kV flit plug joint. (Courtesy NSW Department of Mineral Resources, Mine Safety and Environment).

Photograph 1.



Photograph 2



When an arc between phases occurs a considerable amount of energy is released and the arc can attain temperatures over 10,000 C. The energy input from the arc is dependent primarily on the arc length and fault current.[1] This temperature rise heats and expands the air in an enclosure and also vaporises the metal conductors in the enclosure. The transfer of energy from the arc to the enclosure and its content (including the air or methane air mixture within the enclosure) is very complex. The energy from the arc vaporises electrodes, releases radiant energy, heats and increases the pressure of the atmosphere within the enclosure. (Studies have shown that at least 30% of the arc energy may be transferred to the air/gas in the enclosure, causing a significant pressure rise.) The rise in pressure can exceed the explosion pressure determined in flameproof testing and cause the enclosure to fail catastrophically or to expel hot gases and particles into the surrounding atmosphere.

Short arcs burn mainly in the metal vapours derived from the electrodes. Long arcs burn mainly in the air and the arc voltage is determined by the conditions of the positive column. Arcs in panels will be influenced by both electrode spacing and electrode shape. The arc voltage is generally approximately constant and typical values are given in table 1.

Table 1 Typical arc voltages:[2]

System voltage (Kv)	Clearance distance (mm)	Arc voltage (Kv)
6.6	100 – 150	0.2 – 0.45
11	150 – 200	0.3 – 0.6
22	250 – 300	0.5 – 0.9
33	350 – 400	0.7 – 1.2

Important variables are;

- The free volume of the enclosure.
- Contents of the enclosure (atmosphere, location of equipment, materials used), With regard to location of equipment inside enclosures, it is particularly important that arc sources are not directly aligned with flamepaths where arcing faults can occur.
- The system fault characteristics (two phase fault level, three phase fault level, asymmetry, motor contribution).

Generally, the pressure rise in an enclosure due to fault arcing increases as the volume of the enclosure decreases. As the arc continues the pressure will generally increase, but sometimes it may reach a maximum and then remains constant, especially if the pressure is released through the flamepaths – the issue eventually becomes the destruction of the enclosure due to melting and not pressure.

[1] SIMTARS assessment report No. E 01/0025
[2] Subramanian, S., Vyas, M.K. “Internal arcing & design of metal enclosed switchgear”.

Obviously, if the risk of an arcing fault is minimised, then the risk of a catastrophic failure of an enclosure is significantly reduced. Unless well managed the higher the voltage the higher the risk of an arcing fault. At or below 1200 volts the main problem occurs with the heating effect of load currents, fortunately with today's equipment design and modern electrical protection the risk of arcing faults is felt to be adequately controlled. Whereas at above 1200 volts the problem becomes one of insulation failure due to electric field stresses. This problem with electric field stresses becomes more apparent as the voltage increases. As the voltage increases the industry is venturing into new territory and the effectiveness of risk controls used on lower voltage systems will not be adequate.

Experience has shown that the most common causes of failures in high voltage systems are:[3]

- Voltage stress
- Contamination
- Inadequate insulation
- Mechanical failure

If these issues can be managed properly the risk of a catastrophic failure of a high voltage flameproof enclosure can be reduced to an acceptable level

5. MANAGING THE PROBLEM

The complex nature of the effects of arcing in a flameproof enclosure and how arcing can initiate, necessitates a sophisticated approach to managing the risk. The risk controls will need to consider:

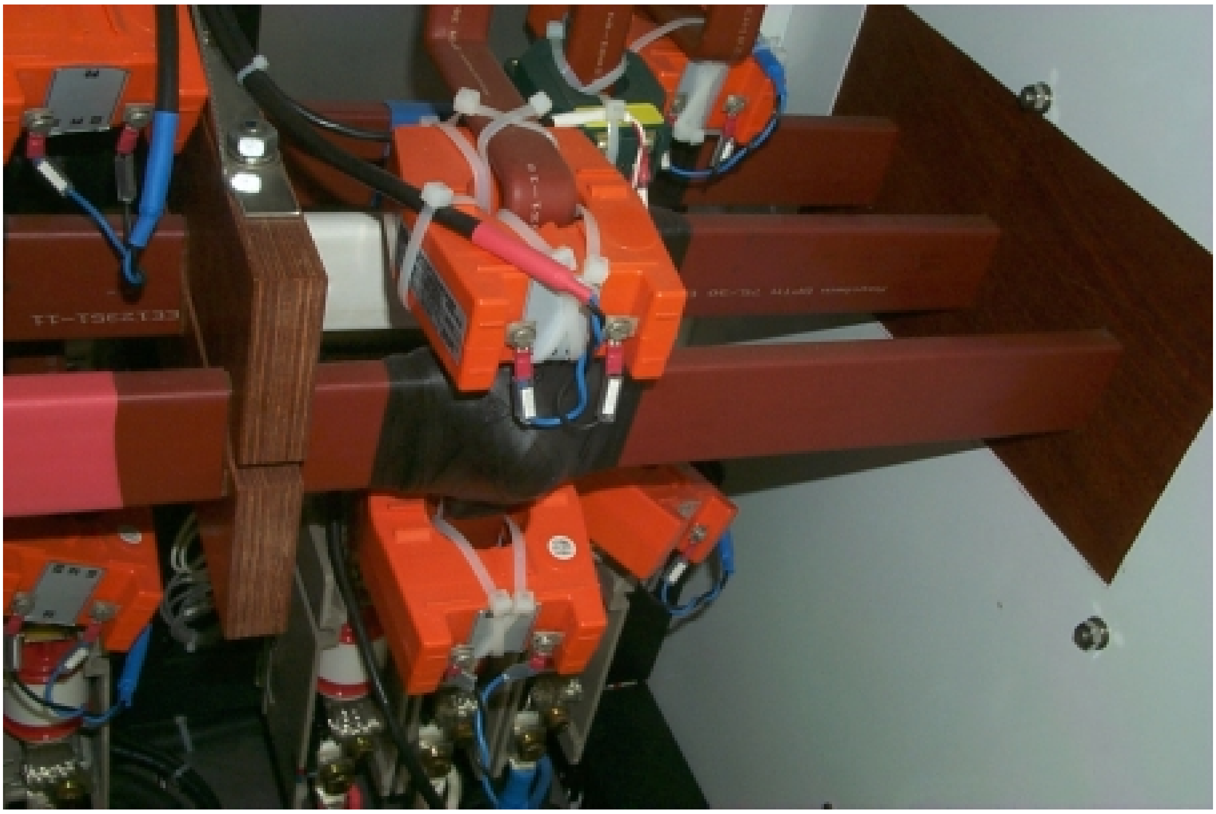
- A thorough analysis of the possible pressure rises in an enclosure under arcing fault conditions. *The calculation of pressure rise in an enclosure is very complex and should only be carried out by an organisation that has the recognised expertise. SIMTARS[4] have done a significant amount of work in this area and are recognised as having the expertise.*
- A thorough analysis of the enclosure and its contents needs.
- The electrical protection strategy, including the type and size of earth fault limitation, the use of sensitive earth leakage, the quick disconnection of short circuit faults, the use of blocking relay systems and distance protection, the use of earth fault lock out protection and back up protection. A prime consideration should be to prevent earth faults from propogating into phase to phase faults by quick acting sensitive earth leakage.

[3] Broadfoot, A. “Management of high energy systems,” p3
[4] SIMTARS = Safety in Mines Testing and Research Station, 2 Smith Street, REDBANK, QLD 4301, Phone 61 7 3810 6300

- Minimising voltage stresses through proper insulation coordination. This includes tape applications at connections, correct application and installation of stress kits, proper clearance and creepage distances. Photograph 3, shows the application of stress kits. Photograph 4 shows the application of insulating tapes at connections.

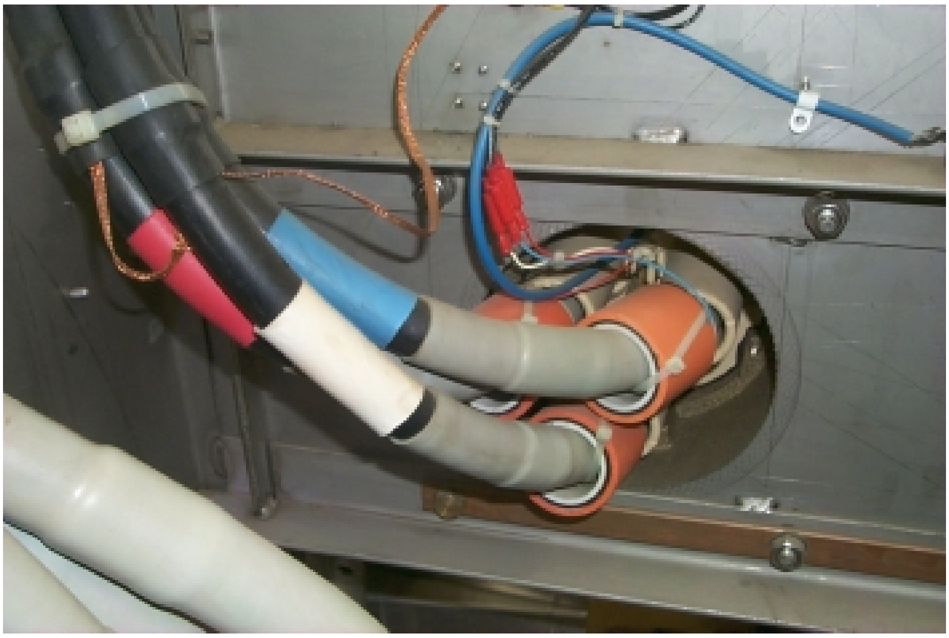
Photograph 3.

Photograph 4.



- Use of earth screens and insulating barriers. Refer to photograph 4 for the use of screens

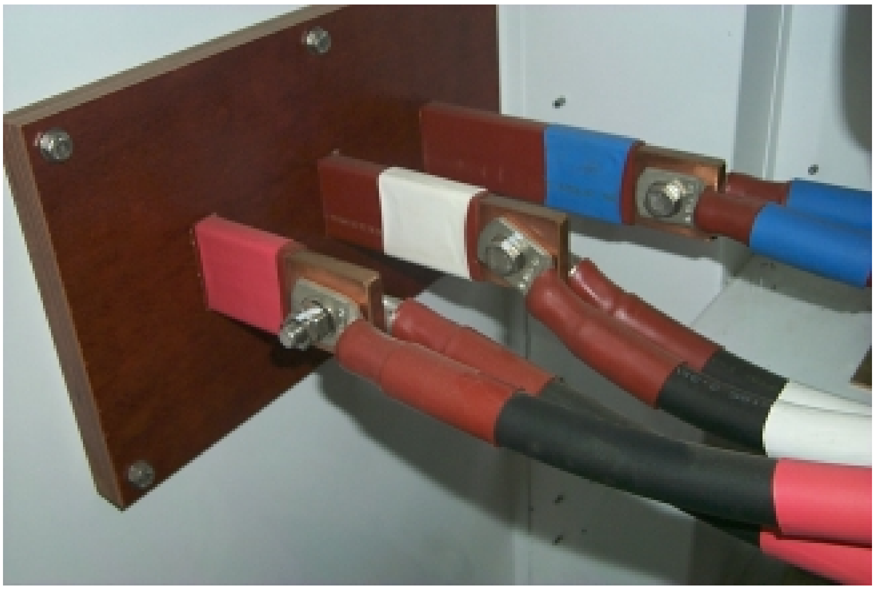
Photograph 4.



- Good physical connections that take into account movement of machines (refer to photograph 5), loose connection prevention by proper torquing (refer to photograph 6), adequate cable/conductor supports (see photograph 3 for busbar supports).

Photograph 5

Photograph 6.



- The selection and location of electrical components within the enclosure, with particular attention to insulation selection and coordination. The possible use of additional barriers such as earthed interphase barriers. The use of increased safety concepts within enclosures. Refer to photograph 7 for location of components.

Photograph 7.

- Take measures to minimise the risk of methane accumulating in enclosures.
- Take measures to minimise the risk of coal dust accumulating in or on enclosures.
- Maintenance practices, especially preventing and cleaning contamination from such as moisture, coal dust, grease, stone dust, oils and so on.

- Workforce competency.
- Change management and review.

6. DATA

6.1 Flame Proof Enclosure Requirements

With the flame proof enclosures commonly used in mines, the generation of pressures, hot gases and sparks are dependent upon an energy source igniting either methane gas, coal dust or in the case of an arc fault, heating the gases to a temperature where expansion of the atmosphere occurs.

As a result of these ignition elements, an explosion can result which also can vaporise or produce volatile components from the materials within the enclosure and further contribute to the pressure rise and leads to the creation of hot and/or gaseous particles.

All these contributions need to be assessed and the following sections detail the ways in which the contributions are assessed and ways to minimise their impact on the pressure rise for the flameproof enclosure.

6.2 Methane Levels

Methane is lighter than air and has a relative density of 0.55. The lower explosive limit (LEL) of a methane air mixture is 5.3% methane. The upper explosive limit is 14%. A level of 7.5% methane is most easily ignited and a methane concentration of 9.8% creates the highest explosive pressure. All tests to determine pressure increase due to a methane explosion are conducted with a methane concentration of 9.8%, as this will provide the highest pressure rise.

Studies that have been carried out by SIMTARS (Safety in Mines Testing and Research Station) actually consider a worst case scenario when simulating arc fault conditions, that is, with the arc fault at its maximum level and the methane in the box set at concentration of 9.8%.

6.3 Coal Dust

- Ingress of coal dust into the enclosure is another source of combustible matter, which, in combination with the arc and with methane, can provide additional burning matter to increase the pressure, it can also be the catalyst for the inception of an arcing fault (particularly in combination with moisture). The size of the coal dust and the type of coal (colour, thickness, density, volatility, ignition temperature) are all characteristics that contribute to the ability of a coal dust explosion to be initiated. It should be noted that Lunn et. al[5]. state:

[5] Lunn, G.A., Rowland, D.B. and Tolson, P. "Electrical ignitions and use of flameproof enclosures in coal-dust

"…It is demonstrated that, in the context of electrical equipment used in mines, coal-dust atmospheres present no risk in excess of that from methane (firedamp) atmospheres…It is unlikely that combustion of coal dust deposits will propagate through a gap of 1mm or less in width and 3mm in length, and gaps designed to methane flameproof standards are unlikely to permit propagation of coal-dust deposit combustion from inside the enclosure to outside…gaps of 2mm width or less are unlikely to permit external ignition by way of individual heated particles; gaps designed to methane flameproof standards are unlikely to permit external ignition of dust clouds or hybrid mixtures in this way…coaldust and coal dust - methane mixtures have safe gaps generally greater than that of methane; gaps designed to methane flameproof standards are unlikely to permit external ignition of coal dust or coal dust - methane hybrid atmospheres by direct explosion transmission…coal dust and coal dust - methane mixtures do not ignite at ignition energy levels below that required to ignite methane."

- Creepage and clearance distances assumed in the electric circuit design can be significantly reduced by the presence of coal dust. The coal dust may be deposited on surfaces, suspended in the atmosphere or may chemically or physically contaminate insulants. A minimum creepage distance in air over the surface of insulation between live conductors and between live and earth conductors is required to maintain rated insulation. Coal dust on an insulation surface introduces an additional tracking medium of conductive dry pollution which will become more conductive in the presence of excessive moisture.

It is important that an enclosure is maintained to minimise coal dust accumulation on insulation surfaces and that preventative measures are taken to exclude excessive moisture. Typical examples are; the physical location of enclosures, anti-condensation heaters for idle plant, and the use of moisture absorbent materials such as silica gel crystals.

In the design of the electrical circuit for an underground coal mine environment, a minimum level of polution should be assumed for all enclosures that are not totally sealed whilst underground. Guidelines for the selection of minimum creepage distances under normal pollution conditions are given in AS3439.1 (IEC 439-1).

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6.4 Short circuit currents and duration

The amount of energy released during a fault within a flameproof box is highly dependent on the magnitude of the power and the duration of the arc. The pressure rise generated is primarily due to the effect heating/burning of the air, similar to a

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and methane atmospheres." Institute of Mining and Metallurgy, Vol 108, January - April 1999, p A71 standard "gunpowder" type explosion. If the duration and magnitude of this arc can be reduced, then the pressure rise can be minimised. SIMTARS in Queensland have developed computer models and provide considerable research into the field of arc faults both experimentally and theoretically.

6.5 Construction of flameproof enclosures and volumes

Testing by SIMTARS has shown that there is a direct link between the net air volume of the enclosure and the severity of the pressure rises during arc fault and explosion conditions. At air volumes within the enclosure 0.21 m^3 or less, the pressure rise due to a gas ignition decreases linearly, but the pressure rise due to an arcing fault increases almost exponentially (this is shown in Figure 1).

Tests conducted by SIMTARS have shown that in vessels with free air volumes greater than 1.0 m^3 high-energy arcs can be maintained without failure of the containment system.

It has been found that the arc fault within small air volumes inside flameproof boxes actually seriously contributes to the increase in pressure rise above and beyond that pressure rise already associated with the combustion of the methane.

6.6 Volatile materials

The other major contributor to an increase in pressure rise due to an arc fault/methane explosion, is a presence of volatile organic materials within the enclosure which upon explosive conditions and arcing, can contribute to pressure rise by burning, ignition of liberated gases or can emit incandescent particles in the event of the explosion which can be transmitted to the outside hazardous area. Also some organic insulants, when in close proximity to an arc may liberate gases that actually increase the arc energy and pressure rise.

Existing good practice would be to remove or minimise all use of organic materials such as polycarbonate, PVC tape, PVC sleeving, rubber insulating putties or other materials which can be considered as being volatile.

It is desirable that all these materials be removed from within the flameproof boxes and replaced with non-volatile materials, or alternatively if this is not possible, then the impact of the volatile materials can be reduced by:

- partial removal,
- relocation away from significant arc sources, or
- covering (eg. taped or epoxied by non-volatile materials (such as glass reinforced polycarbonates, glass tape etc).

The Tables[6] below Summarises the Effects of Commonly Used Insulating materials.

(a) Arcing Only

Vol (m^3)	Nom Volts (kV)	Nom Curr (kA)	CH_4 Coc (%)	Arc Curr (kA)	Arc Dur (mS)	Material	External Ignition	Pres (bar)	Energy (kJ)
0.07	3.3	10	0	12.2 8.9 8.6 7.5 8.6	238 255 255 270 282	None PTFE Bakelite Cement fibre Polycarb	No	6.1 8.4 10.4 17 18.2	2350 3205 3257 2301 4116
0.2	3.3	10	0	9.4 8.9	280 279	None Rubber paint	No	5.7 8.9	2113 2866

(a) Arcing Only cont.

Vol (m^3)	Nom Volts (kV)	Nom Curr (kA)	CH_4 Coc (%)	Arc Curr (kA)	Arc Dur (mS)	Material	External Ignition	Pres (bar)	Energy (kJ)
0.43	3.3	10	0	11.2 8.4 18.2 8.3 10.7 11.3	258 275 277 275 268 266	None Bakelite PVC GRP* Polycarb Metal sheet	No	6.9 9 7.8 7.0 6.2 4.9	4303 4322 4295 4220 4201 3982
0.43	6.6	11	0	11.2 11.5	300 302	None Bakelite	No Yes	5.8 10.1	3587 7768

* Glass reinforced polyester

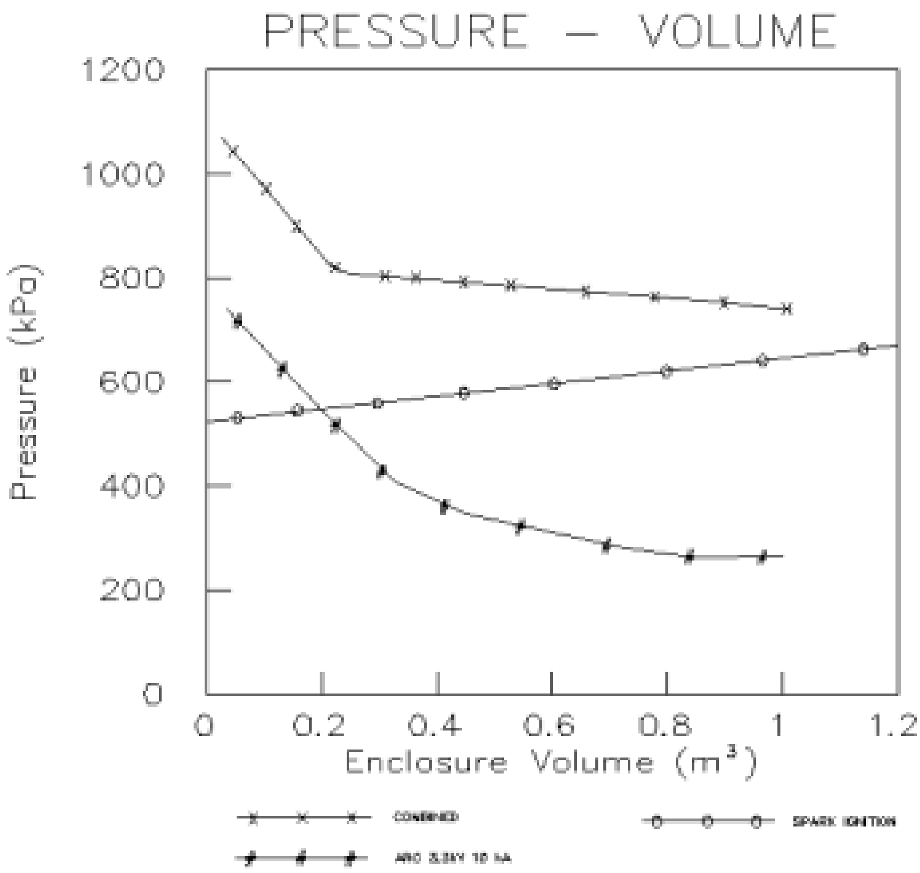
(b) Combined Arcing & gas explosion

Vol (m^3)	Nom Volts (kV)	Nom Curr (kA)	CH_4 Coc (%)	Arc Curr (kA)	Arc Dur (mS)	Material	External Ignition	Pres (bar)	Energy (kJ)
0.43	3.3	10	8.7	9.3 7.7 8.0 7.2 7.8	275 276 276 276 277	None GRP Bakelite Polycarb PVC	No	8.8 9.0 9.4 9.6 9.6	5321 4925 4792 5156 4923

Where organic material must be used, the comparative tracking index should be at least 400 – refer to AS4871

[6] SIMTARS & QUT, "NERDEC Project 1577 - Arc Fault Containment in Flameproof Enclosures (Stage II)", 01/06/1993, Table 6.7.1, p86.

Fig 1 - Pressure vs Volume - Flameproof Enclosure[7]



6.7 Corona discharge

The last major ignition source is due to corona discharge from insulation, discontinuations on terminations or other parts of high voltage equipment. **It is essential that any high voltage terminations are taped, or cold shrunk, with an appropriate material in order to minimise these effects or to provide stress relief termination on all cable connections**. This should minimise any corona discharge and further remove the possibility of ignition sparks due to this phenomenon. Other possible areas of concern are potential transformers where voids in solid insulants have been known to initiate severe discharge.

[7] SIMTARS & QUT, “NERDEC Project 1577 - Arc Fault Containment in Flameproof Enclosures (Stage II)”, 01/06/1993, Figure 6.1, p81.

7. EXAMPLES

7.1 ANALYSIS OF AN 11000 VOLT ENCLOSURE

The enclosure is used in a number of flameproof substations in the mining industry The enclosure has a design rating for 12kV but in some cases it is used at 6.6kV, which gives an increased margin of safety. The transformer enclosure is gas filled and sealed and does not need to be tested. The following data applies to a typical flameproof enclosure:

a. Fault level 2.9kA

b. Enclosure internal free air volume = 0.73 m^3

c. Front and rear door, length of flame path = 44mm

d. Flame path gap = 0.1mm min.

e. Bolt size = 16 mm x " by 32"

SIMTARS Testing Station conducted research/tests on the enclosure. From the tests it was determined that within the flameproof box, a methane explosion and arc fault would result in a maximum pressure of 670 kPa. This assumed a 2.0 kA fault in 9.8% methane/air mixture for a duration of 100 mS. The pressure rise was calculated using their model developed as part of their arc fault containment research work. This pressure rise assumed that all volatile plastics/materials had been removed from the enclosure.

It was then required that a static pressure test be conducted as per AS2380 of 1.5 times the explosion pressure to allow for an acceptable margin of safety. This over pressure test was undertaken and was found that the enclosure held the pressure and gave a maximum width of 0.33 mm when pressurised to 1050 kPa with air. The scope was within the maximum allowable gap 0.5 mm stipulated by AS2380.2.

7.2 ANALYSIS – TRANSFORMER SUBSTATION

Some manufactured substation’s consists of three different flameproof enclosures,

a. The incoming switch (isolator compartment),

b. The main control/power enclosure,

c. The transformer tank.

The transformer tank is air filled and is classed as a flameproof enclosure, as such the transformer enclosure will need to be analysed as well. The following sections detail the data for each individual section of the substation:

7.2.1 Incoming Switch (isolator compartment)

a. Fault level 2.9kA

b. Enclosure internal free air volume = 0.0595 m^3

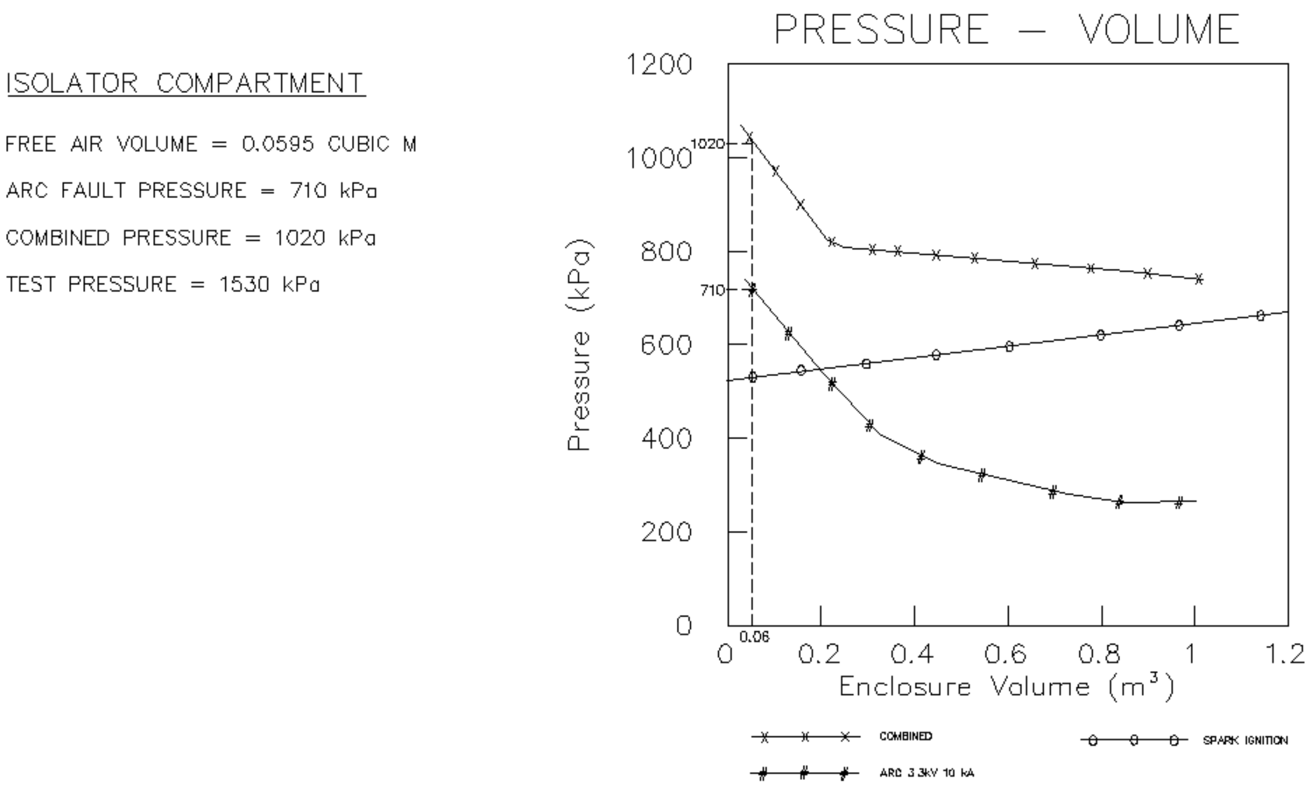
c. Flame path gap = 0.1mm

7.2.1.1 Pressure Rise

Referring to figure 2, it can be seen that the with a free air volume of only 0.06 m^3 (approx.) the isolator compartment would be required to withstand a test pressure of 1530 kPa (based on the minimum pressure rise during arc fault conditions of 1020 kPa).

This enclosure had been tested to 1040 kPa. This enclosure could not be reliably used without additional arc protection techniques as determined by good electrical engineering practice and risk assessment (the techniques selected and the associated risk assessment should be documented). If the enclosure was used without additional arc protection techniques it could not be guaranteed that the enclosure would not fail in a dangerous manner under arc fault conditions.

Fig 2 - Pressure vs Volume - Isolator Compartment[8]



[8] SIMTARS & QUT, "NERDEC Project 1577 - Arc Fault Containment in Flameproof Enclosures (Stage II)", 01/06/1993, Table 6.7.1, p86.

7.2.2 Main Control/Power Enclosure

b. Fault level 2.9kA

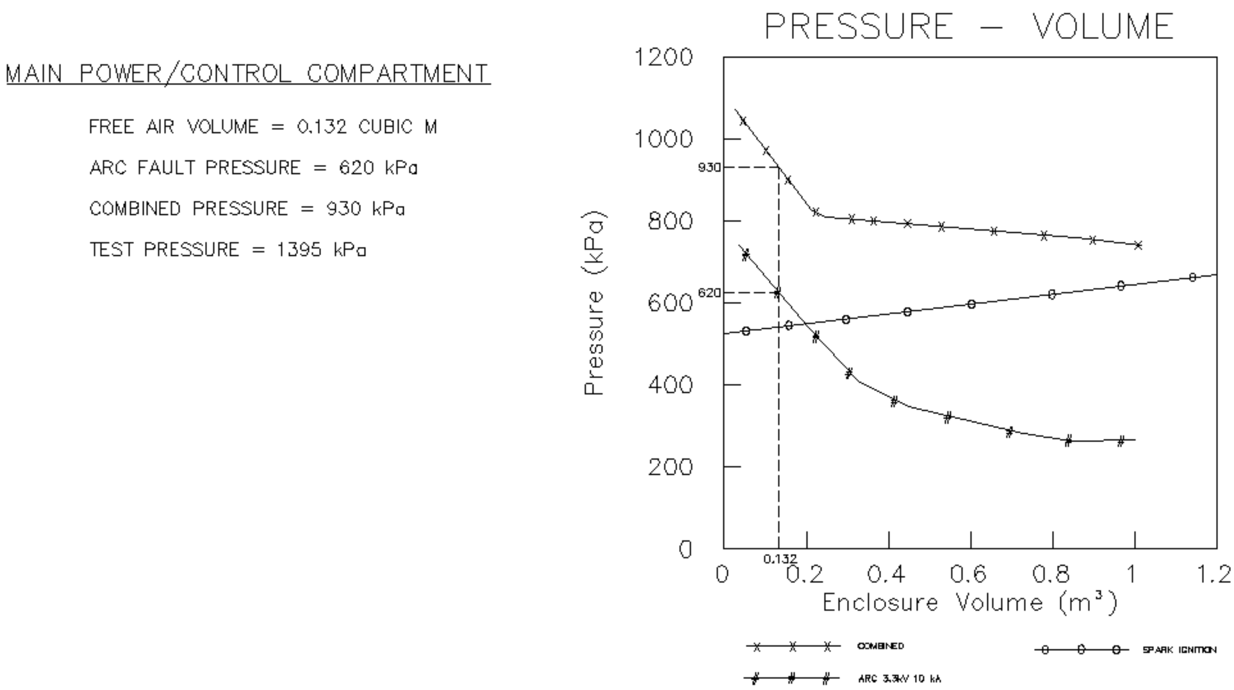
c. Enclosure internal free air volume = 0.132 m^3

d. Flame path gap = 0.1mm

7.2.2.1 Pressure Rise

Referring to figure 3, it can be seen that the with a free air volume of only 0.132 m^3 the Main Control/Power Compartment would be required to withstand a test pressure of 1395 kPa (based on the minimum pressure rise during arc fault conditions of 930 kPa). This enclosure was only tested 690 kPa and it could not be guaranteed that an arcing fault in combination with a methane explosion would be contained safely within the enclosure. This enclosure would need to be re-tested and 1395 kPa, in all likelihood the enclosure would not pass a static pressure test at this level.

Fig 3 - Pressure vs Volume - Main Control/Power Compartment[9]



7.2.3 Main Transformer Tank

b. Fault level 2.9 kA

[9] SIMTARS & QUT, "NERDEC Project 1577 - Arc Fault Containment in Flameproof Enclosures (Stage II)", 01/06/1993, Table 6.7.1, p86.

c. Enclosure internal free air volume = in excess of $2\ m^3$

d. Flame path gap = 0.1mm

7.2.3.1 Pressure Rise

Due to the large internal free air volume of this compartment, there is no concern with pressure rise due to arc faults . Tests conducted by SIMTARS have shown that in vessels with free air volumes greater than $1.0\ m^2$ high-energy arcs can be maintained without failure of the containment system. This enclosure would be deemed suitable for use.

8. RISK CONTROLS

8.1 Electrical technology management systems.

The management of high energy flameproof equipment is very complex and is dependent on the characteristics of the mines electrical distribution system. The following changes are some of the characteristics that will require an analysis of the effect on the high energy flameproof equipment:

- opening/closing of bus ties
- parallel feeds installed
- fault levels from the local supply network
- electrical protection settings, devices and CT's
- motor contribution to fault level
- changes to circuit breakers

8.2 Methane levels

The prime risk control for managing methane levels is a good ventilation system supported by methane monitoring and emergency shut down systems. Irrespective of any history of low methane levels, methane monitoring should be an integral part of the overall strategy for managing the use of high energy flameproof equipment.

The methane content allowable, and location of methane monitors is generally prescribed in legislation. Effectively if the methane concentration in the general body of air exceeds 1.25%, all power must be turned off to electrical equipment that is not intrinsically safe.

Generally higher voltage flameproof equipment is located in intake air. This is significant as this is the point of lowest methane levels because the air has not yet had a chance to pass through the exposed face where methane concentrations are usually the highest. This ensures that the methane levels remain relatively low in proximity to the flameproof enclosures. Even so, consideration should be given to having alarm/trip levels set at 0.5% and the provision of redundant methane monitoring systems. The mine management systems must be able to provide documentation regarding the monitoring of methane levels within the flameproof box areas and ensure that both primary and back up systems are functional and should trip the outbye high voltage supply once the methane level has reached 0.5% over the transformer.

If the high voltage flameproof equipment is located in any location where methane and/or coal dust liberated during production can pass over it, it is essential that a thorough assessment be made by an organisation with the recognised expertise.

8.3 Coal dust levels

It is essential that the mine management ensure that the levels of dust within the flameproof enclosures be minimised by suitable housekeeping procedures. These could include:-

Regular cleaning of all flameproof faces and panels during inspections.

Procedures to ensure that coal dust build up on the outside of enclosures is minimised.

Regular cleaning of the internals of the box during inspections.

Ensuring that the flameproof path surfaces are clean and sealed and within accepted tolerances.

The application of suitable greases on all flamepaths.

These points will ensure that the ingress of dust into the cubicles is minimised.

As mentioned in the previous section, most flameproof equipment is located in the intake airway, where this is not the case the inspection and cleaning regime for the purpose of maintaining a dust free enclosure must be far more rigorous.

It is also important to realise that dust control at conveyor transfer points etc ., contribute significantly to reducing the amount of dust available to be deposited on the high voltage flameproof equipment, and if this dust control is compromised then it may increase the risk of dust accumulation inside the enclosures.

The mine management must put procedures, systems and work instructions into place in order to minimise or eliminate the possibility of coal dust or other ignition sources from penetrating into or onto the flameproof enclosures. Regular test/inspection procedures should be implemented and incorporated into the current maintenance activities (refer to AS2290.1).

The mine management system must ensure that the ventilation system is adequate and the level of particulate in the stream around the flameproof enclosures is minimised. Additional ventilation may need to be installed to change or augment the existing system.

8.4 Electrical protection

A full fault level/protection study complete with protection curves, settings and maximum-tripping times should be undertaken. This should include fault contribution from large induction motors or numbers of motors. However, the study must also take into account the large current rises due to the start up of the Shearer, AFC and the other Longwall drives.

It is essential that the mine management system ensures that the protection systems/settings are able to clear a fault in a minimum amount of time, consideration will need to be given of the “pick-up” time and the circuit opening device opening time. Basically there is a need to limit the arc fault duration to a time that prevents excessive pressure rise and at the same time not adversely affect other forms of protection within the system. This must be extended to the back up protection, in the case of failure of the primary protection.

It may be necessary to consider reducing the available fault energy by fault limiters / current limiting fuses so that the fault arc is extinguished within the first quarter cycle.

There will be a need to review the fault configuration of the mine electrical system if the existing fault level is exceeded at some time in the future due to either relocation of the Longwall face or to increases in the strength of the electricity supply by the relevant supply authority. This will affect the results of this type of analysis and these changes should initiate an immediate review.

The mine management must put procedures, systems and work instructions into place in order to provide regular checking of the electrical system electrical/electronic protective devices settings. It is suggested that this be incorporated into a relevant maintenance and inspection practices for these devices. It is further recommended that primary current injection be performed on the protective devices periodically to ensure all are within the manufacturers operating parameters.

The protection scheme has to consider earth fault limitation in conjunction with sensitive earth leakage protection and earth fault lock out to prevent reclosure onto a fault.

Earth fault limitation should be via an earth fault limiter in the system neutral – refer AS2081. Recommended limitation levels are 5 amperes, 10 amperes and 25 amperes, although 50 ampere values have been considered. As system capacity requirements increase it may be necessary to increase these levels to as high as 200 amperes. Note: the higher the limitation the more need to consider the effects of arcing to earth. The sensitive earth leakage current trip setting should be at most 10% of the value of the limitation. The trip time setting should be as quick as possible so that the possibility of the earth fault developing into a phase to phase fault is minimised.

Note: It is preferred that earth fault limitation be predominantly resistive so that the possibility of high voltage transients and resonance are minimised. With the transition to XLPE cable resonance effects due to reactive earth fault limiters and higher cable capacitance may become a problem.

8.5 Flameproof enclosure construction

Ideally the free volume should be such that excessive pressure rises are unlikely.

SIMTARS have identified that a free volume greater than 1 cubic metre will not have pressure rise problems due to arc faults.

8.6 Content of flameproof enclosures

Good practice would be to remove or minimise the use of organic materials such as polycarbonates, PVC tape, PVC sleeving, rubber insulating putties or other materials which can be considered as being volatile.

It is essential that all these materials be removed from within the flameproof boxes and replaced with non-volatile materials, or alternatively if this is not possible, then the volatiles be covered, taped or epoxied by non-volatile materials (glass tape etc).

Particular care may need to be taken with regard to potting compounds used between two enclosures. This compound should not liberate combustible material during arc faults and its physical integrity must not be compromised under the effects of increased pressures due to arcing faults.

Equipment should be selected, designed and installed to minimise the possibility of an arc fault developing (an example may be earthed phase barriers or insulated barriers designed to increase the clearance distance– refer AS4781. Consideration to using increased safety concepts within the flameproof enclosure should be given

Equipment located inside the enclosures should be positioned so that potential arc initiation sites are not aligned with flamepaths and gland openings – so that arc products do not have a direct path to the outside atmosphere.

Possible arc fault sites should not be in a location where a similar affect as “pressure piling” can occur.

The free air volume within the enclosures is critical. Under no circumstances can mine management reduce the free air volume of the enclosures by the incorporation of new devices, or other equipment, without a review of the impact on arc fault integrity of the enclosure.

When repairs and/or component replacement are undertaken on the equipment it must be recognised that the size and composition of the materials used may have a negative effect on the effectiveness of arc fault control. There must be a management system in place to highlight any changes and to alert the relevant personnel such that the arc fault control properties can be re-verified with the new parameters.

8.7 Insulation integrity

The correct insulation levels must be selected and maintained.

It is recommended that all terminations within High-tension enclosures be taped with a suitable HV tape. (Scotch 23 or equivalent would meet this requirement)

A transient voltage analysis should be conducted to determine whether the insulation can be compromised – refer AS1824-1995 for guidance on insulation coordination. Particular care needs to be taken where vacuum contactors or circuit breakers are used (these should have contact design that minimises the effect of current chopping).

It needs to be recognised that partial discharge and the resultant deterioration of insulation constitute a prime cause of insulation failure at higher voltages (there have been plenty of examples of partial discharge leading to failure of electrical equipment in coal mines at voltages of 11kv. The partial discharge can initiate internally in solid insulants or on the surface through tracking. High CTI insulants and good maintenance practices must be used to prevent surface tracking. Good quality solid insulants are essential to prevent partial discharge in internal voids of solid insulants and in such equipment as potential transformers.

8.8 Other

A training awareness system shall be implemented in order to make all personnel aware of the extra requirements and care that needs to be taken with the "housekeeping", maintenance, operation and repair of the Longwall System.

The collieries Management Systems, for re-powering the Longwall after ventilation failure, are reviewed to ensure that confirmation of gas levels within the High-Tension enclosures & within their vicinity, be confirmed before energisation of the High Voltage supply is undertaken.

8.9 Motors

As machine power consumption increases, there is a need to ensure that the electrical distribution system can deliver the required levels of power, this invariably means an increase in fault level and consequently available arc energy at motor terminal boxes on such machines motors as AFC, crusher, stage loader, hydraulic pumps and shearers. The motor terminal boxes should be constructed to an increased safety level at least, where the terminal boxes are flameproof the relevant features of increased safety should be incorporated.

APPENDIX A

Management of high energy systems

Dr Alan Broadfoot

Dr Alan Broadfoot
B.E. (Hons), M.E., Ph.D., M.I.E.E.E., F.I.E.Aust.

Ampcontrol Pty Ltd

2. INTRODUCTION

There has been a steady increase in demand for energy in underground coal mines since mechanisation. This has been a natural outcome of increased demands on coal supply as the world's population increases and industrialises.

The initial underground utilisation voltages were between 32V and 415V [Figure 1]. These have progressively increased through 1kV to 3.3kV while distribution voltages have increased from initially 2.2kV through 6.6kV to the present Industry Standard of 11kV. Overseas 22kV is already being used and presently in Australia investigations are under way for face voltages of 11kV and distribution voltages of 33kV [Figure 2].

Figure 1 - Typical 415V LT End used in late 1970's

Figure 2 - 11/3.3kV 6MVA Longwall Substation

The steady increase in voltage results from the need to increase the power supply to machines whilst keeping distribution cables to manageable sizes. Ultimately however, it is the quality of the power supply in terms of its energy rating rather than its voltage level that determines on-load voltage regulation at the point of utilisation and the resulting productivity levels.

Higher voltages reduce transmission losses and therefore improve the efficiency of power systems. However, it is the load to fault level ratio at the point of utilisation that determines machine productivity by maintaining the terminal voltage of motors at a value close to nominal.

However, the ever increasing demands on supply is reducing the safety margins on equipment and work practices as required fault levels to maintain efficient operation of machinery approach the limits of the equipment rating. Also, the probability and consequences of risk associated with the higher energy levels are correspondingly increasing placing more urgency on the development of the quality of engineering practices and risk management of high-energy systems.

3. THE ISSUES

The issues of engineering practice and risk management associated with the use of high-energy systems within the confines of a coal mine are many. In this paper some of the more critical issues are to be considered. These are:

i) Design considerations for arcing faults

ii) Effects of over-voltage transients associated with high capacitance systems

iii) Fault limitation and earthing

4. INTERNAL ARCING

3.1. Fault Causes

The most probable causes of failures in the high voltage system are:

- Voltage stress
- Contamination
- Improper installation
- Mechanical failure and/or movement

Voltage stress or surges can arise from previous system faults, switching and/or switched capacitance. This is discussed further in a separate section of the paper.

Contamination can result from moisture, coal dust, stone dust or grease. Contamination can cause a fault directly by allowing a conductive path to form, or indirectly by causing overheating.

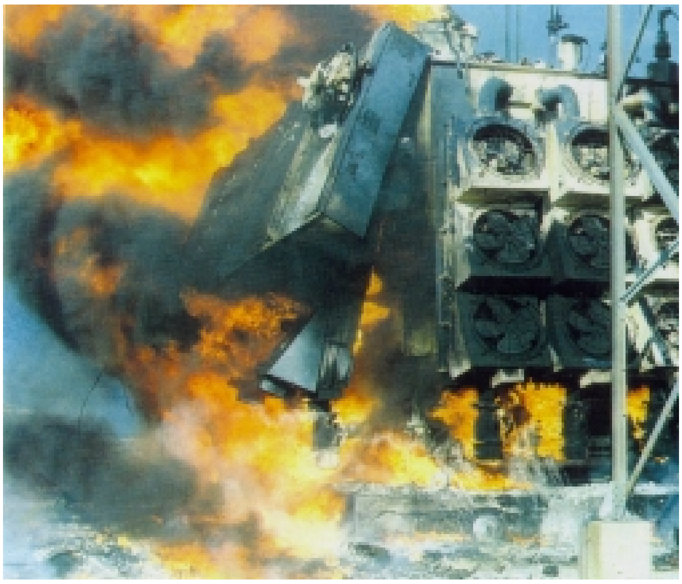
Improper tape application in connections, incorrect installation of stress kits, use of wrong size lugs, inadequate clearances or loose connections due to incorrect torquing can all lead to fault.

Mechanical failures due to moving the equipment, vibration or bearing failures on motors can all result in insulation failure.

3.2. Available Fault Energy

The temperature of an electrical arc is over 10,000°C. A high-energy arc raises the pressure in an enclosure by heating the air and vaporising the metal conductors inside the enclosure. Copper expands by a factor of 67,000 in vaporising. Understanding the nature of the fault is extremely important in controlling the arc [Figure 3].

Short circuit and co-ordination studies are commonly performed considering only bolted three phase or phase to ground faults. However, real life equipment failures rarely are bolted faults. In fact, the fault that causes the most current to flow (the bolted fault) involves no arcing and dissipates fault energy throughout the distribution system resistive elements. However, an arcing fault releases large amounts of energy at the point of the fault and is the greatest risk to equipment and personal safety.



8.9.1.1

Figure 3 - High Voltage Equipment Failure

The energy relevant in the arc is given by:

$$E = V_d \, I_f \, t_{arc} \text{ (Wattseconds)}$$

where V_d = rms voltage drop across the arc
I_f = rms fault current
t_{arc} = time duration of the arc in seconds

Note that the arcing current is less than the bolted fault current since the arc voltage drop subtracts from the system voltage during the fault current.

The use of a high resistance earthed system does minimise the amount of damage created from the fault by the following:

- It reduces the fault current to some smaller value typically 10-25 Amps. The I^2t for a 10 Amp fault is 1/10,000 of a 1,000 Amp fault assuming an equal amount of time (t). Therefore, using high resistance earthing drastically reduces the energy normally dissipated in an earth fault.
- It creates a voltage drop across the neutral earthing resistor resulting in the remaining voltage at the point of the earth fault being significantly reduced. Therefore a sustained arcing fault is not likely.

The use of high resistance earthing in the coal mining industry therefore creates the opportunity to manage the risk by the prevention or control of the phase to phase arc rather than the need for arc containment.

3.3. Pressure Rise due to the Fault

The pressure rise due to an arc is due to heating of the air surrounding the arc and the heating and vaporising of conductors and other metal conductors. Primarily heating of the air causes the initial rise of pressure rise, but the percentage of total arc energy used for vaporisation of conductors and other metal increases rapidly with time after the arc is initialised. However, based on studies approximately half the arc energy is available for warming the air.

The general observations that can be made in regard to the enclosure pressure rise due to a fault is:

i) Pressure rise increases as the enclosure volume decreases

ii) Pressure rise increases as arc duration increases. The use of current limiting fuses to interrupt current in 0.25 cycle is beneficial in reducing the released fault energy in the enclosure and the resulting pressure rise.

iii) For extended fault durations, it is difficult to construct an enclosure with sufficient mechanical strength to contain the pressure generated by a fault in the enclosure.

These observations form the basis of any risk assessment for controlling the changes of an arcing fault.

3.4. Risk Management

It is virtually impossible to design and install an electrical system that will prevent all faults. Therefore a quantitative risk assessment must be made to priorities and optimise safety related investment. That is, practical precautions need to be taken to manage and reduce the danger to personnel and damage to equipment from the high levels of energy released in a fault.

The items to be at least considered in the management scheme are:

i) Phase to phase arc preventative design
ii) Structural and pressure relief design of enclosures
iii) Employee awareness and operating procedures
iv) Preventative maintenance
v) Operator location
vi) Insulation levels and co-ordination
vii) Larger size enclosures
viii) Cable supports
ix) Proper sealing of enclosures
x) Reduction of available fault energy with current limiting fuses

In preventative design it is possible to determine critical arcing voltages for various air gaps in a methane explosion. A type result is given in Figure 4.

This can be used to prevent the risk of a methane explosion/electrical arc rather than designing the enclosure for the combined pressure.

The other items are all self-explanatory and can be used to minimise the risk and the damage of a high-energy release.

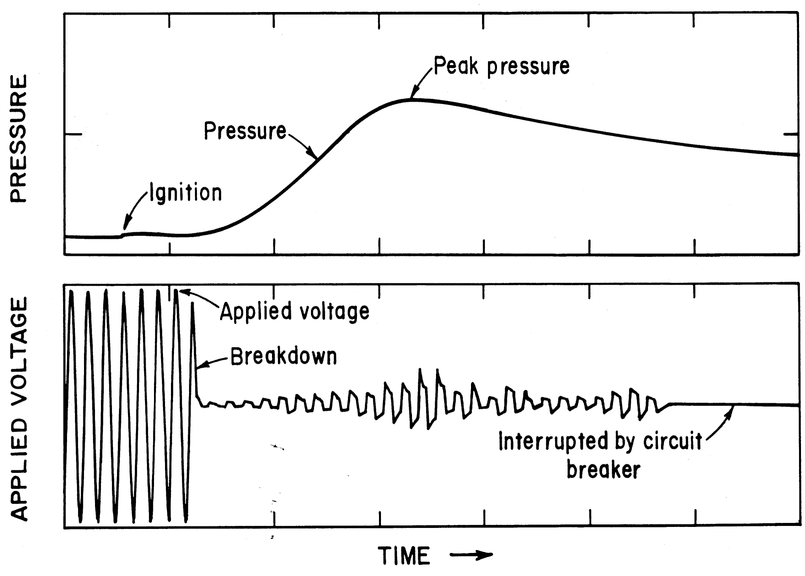


Figure 4 Oscillograph of a Self-Sustaining Arc.

5. OVERVOLTAGE TRANSIENT

4.1. The Problem

Transient overvoltages are due to natural and inherent circumstances of power systems. Overvoltages may be generated by a sudden change of system conditions (such as switching operations, faults, load rejection etc). The magnitude of these overvoltages can be above maximum permissible levels and therefore need to be reduced and protected against if damage to equipment and possible undesirable system performance can be avoided [Figure 5].

8.9.1.2 Figure 5 - HV Open Cut Installation

The occurrence of abnormal applied voltage stresses either transient, short time or sustained steady state, contributes to premature insulation failure. Electrical organic insulation deterioration to the point of failure results from an aggregate accumulation of insulation damage that finally reaches the critical stage. That is, the problem is complicated by the fact that insulation failure results not only because of impressed overvoltages, but also because of the aggregate sum total duration of such overvoltages.

For example a large fraction of the insulation system's capability to withstand applied voltage can be destroyed simply by the process of testing it. For this reason over-testing with dynamic AC voltage should be avoided. A 30% increase in the applied AC voltage magnitude for most equipment will result in a ten-fold reduction in insulation life.

4.2. The Surge Environment

The availability and use of new and improved materials and devices associated with higher energy systems and the desire to produce cost-effective competitive products has resulted in greater exposure of the electrical system, especially motors and transformers, to high amplitude steeper front voltage surges. Some examples are:

i) Increased use of vacuum switchgear. These produce repetitive high amplitude, steep fronted surges during closing as well as opening operations

ii) Use of low loss cables that do not attenuate the surge.

iii) Motors are started and stopped more frequently to achieve operational economics.

iv) Increased power densities due to improved technologies and the need to reduce losses have resulted in equipment that are less conservatively designed. Some manufacturers do not use dedicated turn insulation when not required by specification. The strand insulator is now designed to function as the turn insulation.

4.3. Factors affecting surge Amplitude and Rise Times

The problems relating to the achievement of insulation security for turn to turn insulation in multi-turn coils are many and complex. The normal 50Hz voltage developed in a single turn will range from perhaps a small fraction of 1V in a contactor magnet coil to 20V in a medium sized induction motor to several hundred volts in a large transformer. If it were necessary to only insulate for the normal operating voltage developed in a single turn, the problem would be simple. However, the voltage stress that appears across a single turn to turn insulation element when high rate of rise voltages surges occur may be much greater than the single turn operating voltage.

This aggravated voltage stress is most pronounced at turn insulation adjacent to the coil terminals and is intensified by the increased shunt capacitance between winding sections and earth, such as exists inherently in motor windings as a result of each coil in the construction being surrounded by earthed stator core iron. In addition the safety margins on insulation are reduced especially for rotating machinery due to space limitations, performance and economics. These limitations on insulation, voltage stress between turns of multi-turn coils becomes critical for higher energy systems.

Switching in vacuum produces multiple surges during closing (pre-starts) and opening (re-ignition). Hence, for a single event of opening or closing, the vacuum current produces multiple surges and therefore stresses the turn insulation more than other switching. Further, multiple re-ignitions cause each successive surge to be at a level higher than the previous one

The time duration over which the pre-strikes can occur and the number of pre-strikes possible during a breaker pole closing are functions of the system and motor voltage. The higher the voltage, the greater the distance the contact or pole has to travel, and the greater the distance over which the dielectric strength of the gap can be exceeded by the applied voltage.

The type of motor to contactor cable used and the manner in which it is earthed has an effect on the amplitude and rise time of the surge arriving at the terminals. The lower the loss in the cable, the lower is the attenuation of the surge. Typically if the cable is long, the greater is the attenuation of the surge. However, with the modern low loss cables (for example EPR) practically no attenuation of the surge takes place, irrespective of the length of the cable.

6. EARTHING

5.1. Design Considerations

Resistance earthed systems employ an intentional resistance connection between the electric system neutral and earth. This resistance is actually in parallel with the system to earth capacitive resistance. The zero-sequence network for this is shown in Figure 6. The problem is if the intentional resistance connection is too high there will be a delay in establishing an earth return current sufficient to trip the protection relay while the cable capacitance charges. In addition, in the period of delay transient overvoltages of up to 73% could occur due to the overvoltage tendancies of a purely capacitively grounded system.

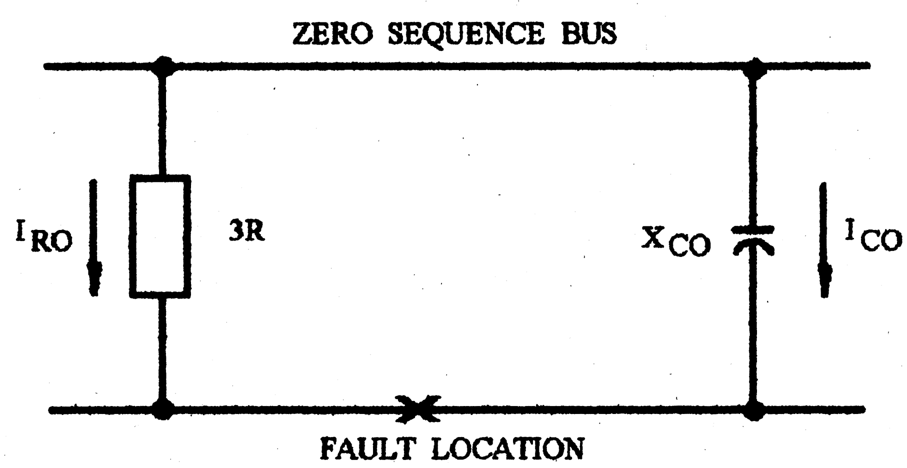


Figure 6 Zero-Sequence Network of High-Resistance Grounded System

The ohmic value of the resistance should be not greater than the total system to ground capacitive resistance ($X_{co}/3$). The neutral resistor current should be at least equal to or greater than the system total charging current. Consequently, at higher voltages, with the larger cable charging current, lower resistance grounded systems are required.

5.2. Higher Harmonic Currents

More and more there is connection of rectifiers, DC drives and other electronic switching devices to the power system. Without the drives, the capacitive current at 50Hz is normally a positive sequence value under steady-state conditions, and the currents cancel. However, many drives create a zero-sequence voltage and when coupled with the earth, will cause a high frequency zero sequence current to flow in the neutral earthing resistor. This can result in the following problems:

- Nuisance trips due to increased rms current
- Resistor sizing problems due to the heating effects caused by the harmonic current flow.

5.3. Other Issues

Some other issues on earthing currents worth commenting on are:

- For voltages in excess of 11kV the industry will need to adopt multi-earthing practice rather than single point because of the higher cable charging currents and consequently higher value limitations required to prevent transitory overvoltages. Typically for a 33kV system the fault limitation would be 200-300 Amps.
- With higher earth fault currents the concepts of equipotential work zones, electrode earthing and earth fault clearance times must be applied.
- The permissible reduction in available earth fault current without risk of transitory overvoltages is limited for reactance earthed systems. The criteria for curbing the overvoltages is that the available earth fault current be at least 25% of the three phase fault current. [IEEE Standard 141-1993]. This guideline would exclude the use of reactors in coal mines.