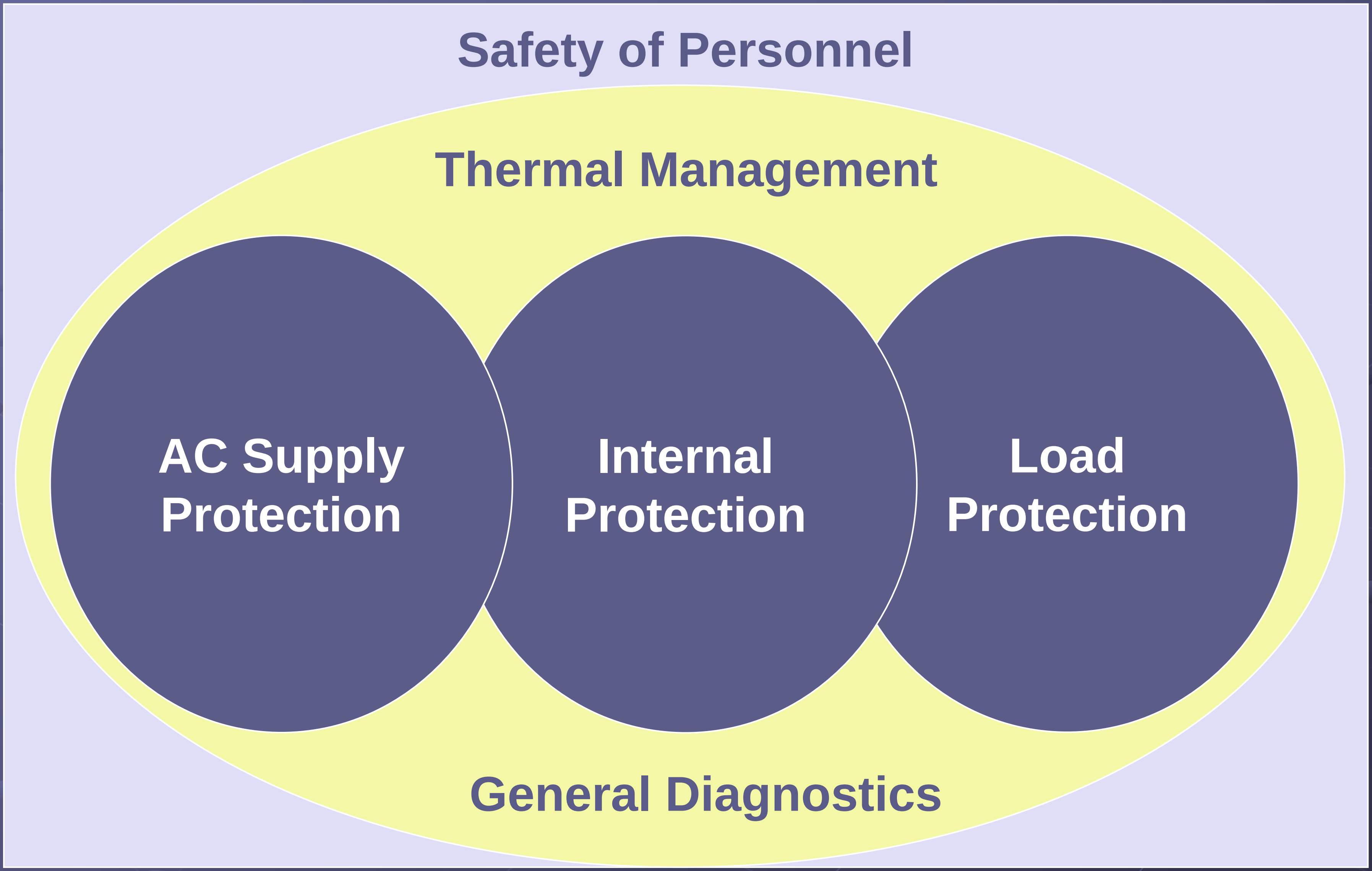
Protection, Interlocks and Diagnostics

By

Steve Griffiths

Protection Overview



Safety of Personnel

Safety of Personnel

Equipment must be designed, built and tested to the appropriate standards.

Covers the supply voltage ranges 50V to 1000V ac rms or 75V to 1500V dc.

Equipment provides a high level of protection

Conformity with the Low Voltage Directive (LVD) is mandatory.

There is no dedicated safety standard for power converters

Scope
Safety of persons & property
Consistency of control response
Ease of maintenance

Useful references:
BS EN 60204 Electrical safety of machines.
IEC 60950 Safety of information technology equipment.

Steady state voltages upto 42.4V peak, or 60V DC are generally regarded as hazardous under dry conditions for an area of contact equivalent to a hand!!!!!!

Safety of Electrical Equipment

Definition

- Considered safe if no accidental contact with any live or potentially live components can be made.

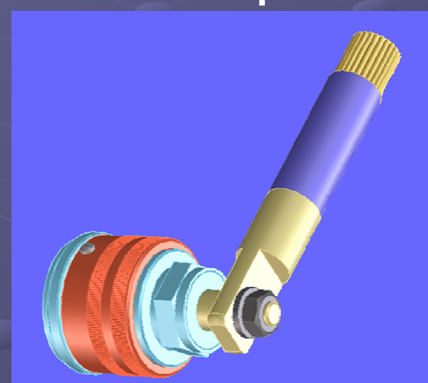
How is it achieved

- Enclose all converters in earthed metallic cubicles.
- Guard the input and output connectors with appropriate covers.
- If the cubicle is opened the input supply must disconnect automatically.
- Larger equipment will require a separate enclosure and adequate protection.

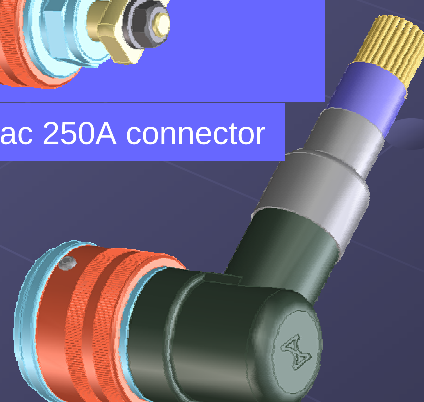
Protecting Personnel

Metallic Housings

Output Terminals



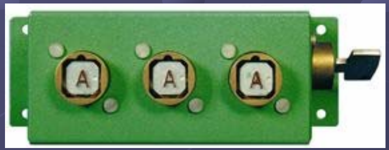
Hypertac 250A connector



Safety Signs

Cubicle Protection

- Microswitches on removable covers or doors.
- Specialist key arrangements.



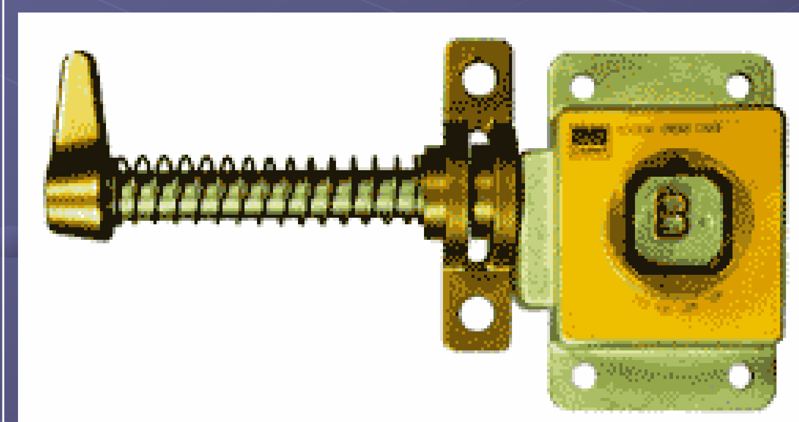
- Access delays to enable discharge of energy storage devices.
- Resistive earth sticks – providing secondary protection only.

- Access to Authorised personnel only.

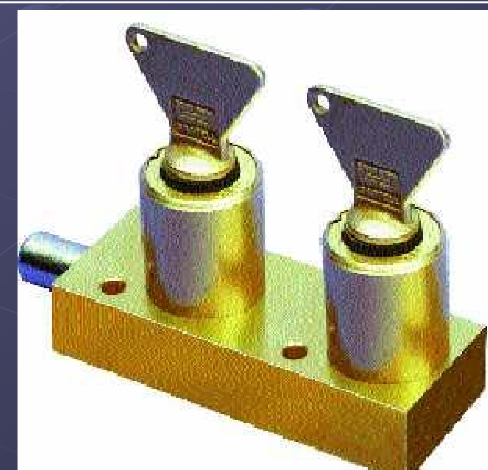
Specialist Key Arrangements

Key Exchange Box

Key Exchange Box



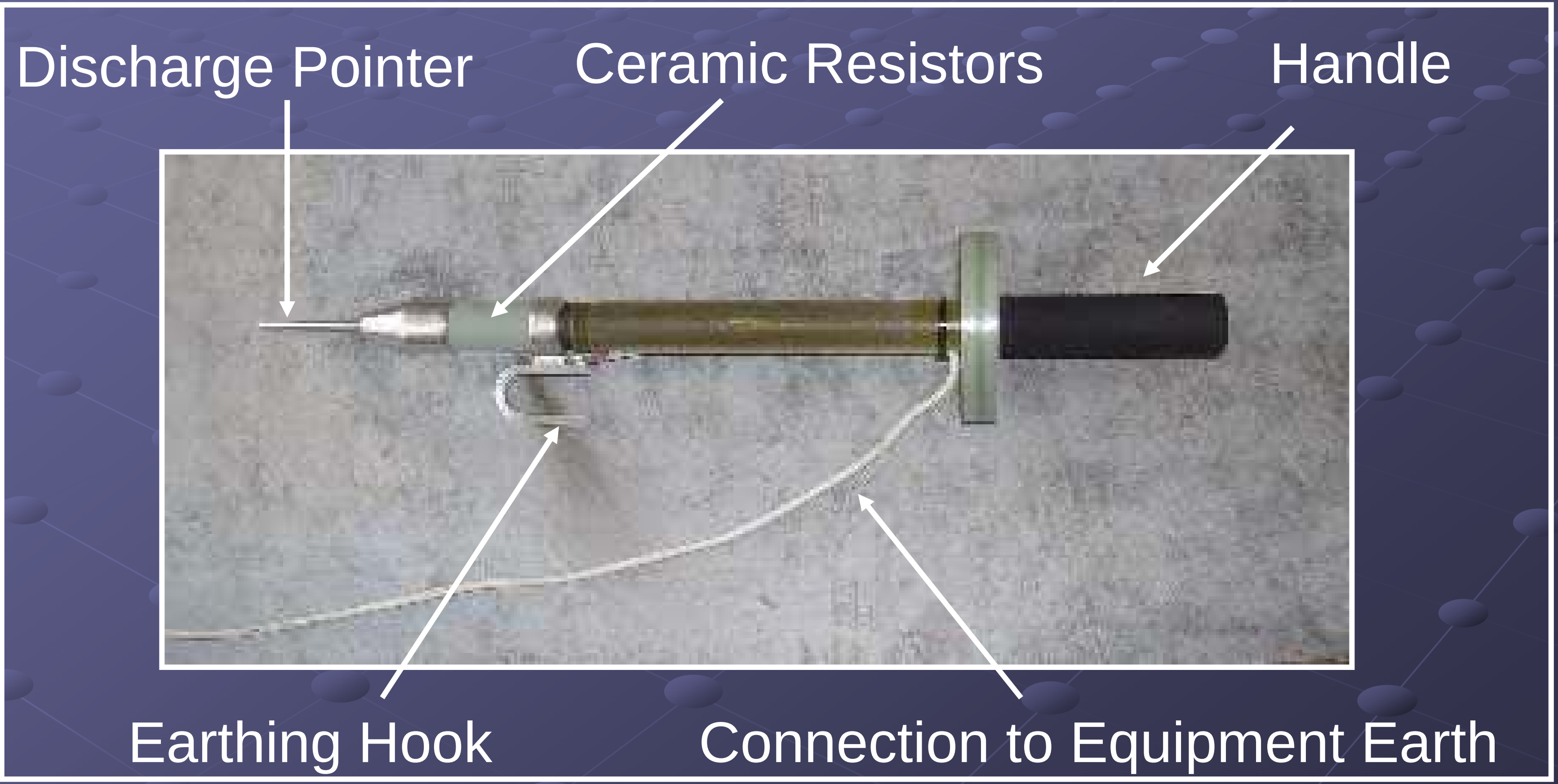
Single Key Interlock



Double Key Bolt Interlock

Earthing Sticks

Rating plate must indicate - Discharge Voltage and Energy



Safe Working Practices

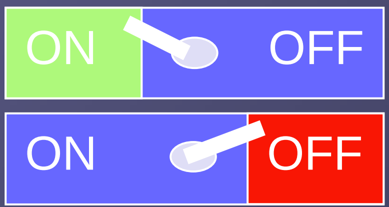
- All accelerators must have their own dedicated safety procedures.
    - Listing control measures to minimise risk associated with all identified hazards.
- General electrical precautions

    - Isolate the equipment from all sources of supply
    - Prevent unauthorised connection or operation by fixing safety locks and caution notices at all points of isolation.
    - Discharge the installation.
    - Where practicable prove dead, with voltage test indicator at all points of isolation and at the places of work.
    - Where practicable earth the incoming terminals.
    - Never work alone.

General Electrical Precautions

Authorised Person
(Accompanying Person)

Isolate



Daresbury Laboratory

Discharge

Steve Griffiths

Prove Dead

Earth
(if possible)

Personnel Safety System

- Often accelerators have limited access areas when the magnet loads are energised.
- This is the case when:
  - the magnetic fields are very high,
  - the zone is exposed to radiation when the accelerator is working or
  - the busbars of the magnets are not protected.
- Access is allowed only when the power converters are turned off.
- This interlock system is usually integrated in a more complex general access system.

Live Working

- At some stage during the life of equipment live working may be necessary and appropriate action should be taken to minimise the risk.
- By designing equipment with effective diagnostics and protection, live working should be reduced.

- A typical regulation is that no person shall be engaged in any work on or near any conductor where danger may arise unless:
  - It is unreasonable in all the circumstances for it to be dead and
  - It is reasonable in all the circumstances for him/her to be at work on or near it while it is live and
  - Suitable precautions (including where necessary the provision of suitable protective equipment) are taken to prevent injury.

- Live working is discouraged and is normally a last resort.

Thermal Management

Modern Accelerators

- Quad, Sext and Corrector magnets are usually powered independently.
- Increased demand for compact, low power modules.
- Connection in series and / or parallel configuration for high power applications.
- More localised instrumentation areas containing large numbers of low power modules.
- Excessive temperature accounts for 55% of all electronic equipment failure.
- Main cause of overheating is a result of the ongoing drive towards miniaturisation.

Thermal Management

- Energy passing through a converter produces losses and creates heat.
- This heat will not be evenly distributed.
- Heat must be removed from the unit and surrounding area.
- Designer - procurer considerations:
  - Performance
  - Space available
  - Topology
  - Environment
  - Cooling method
  - Component layout

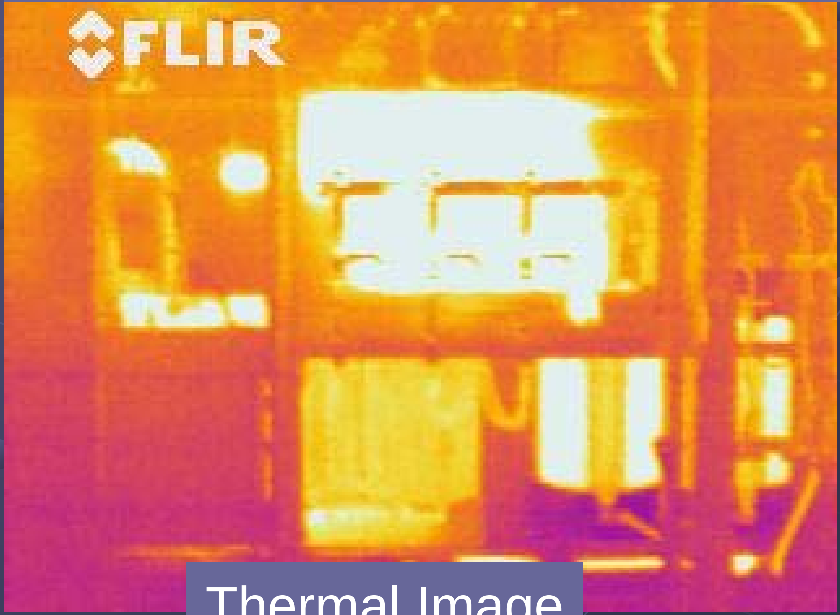
Linear
Thyristor Controlled
Switchmode

Air natural
Forced Air
Water

Forced cooled switchmode unit

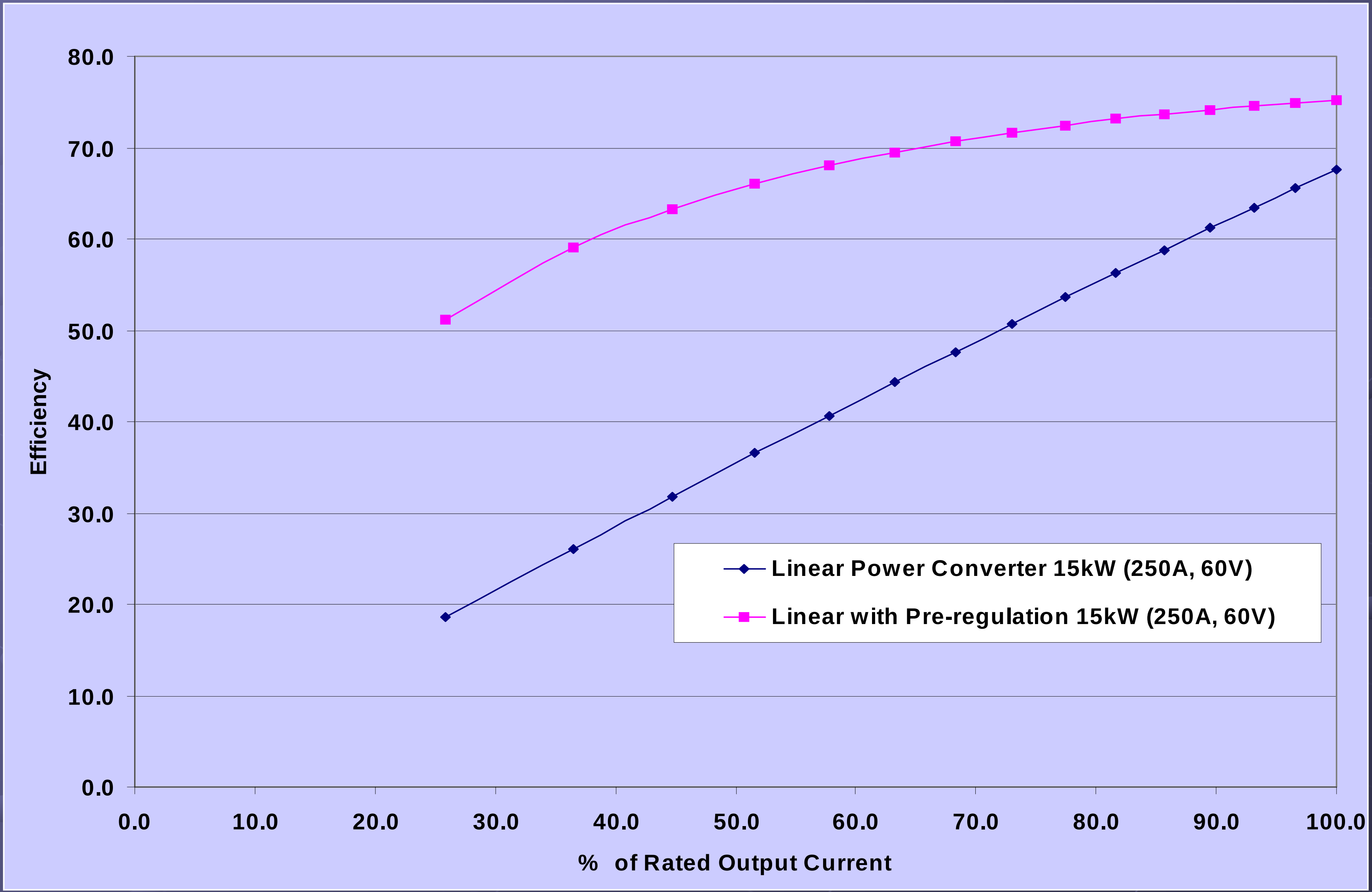
Natural cooled thyristor controlled unit

Thermal Image

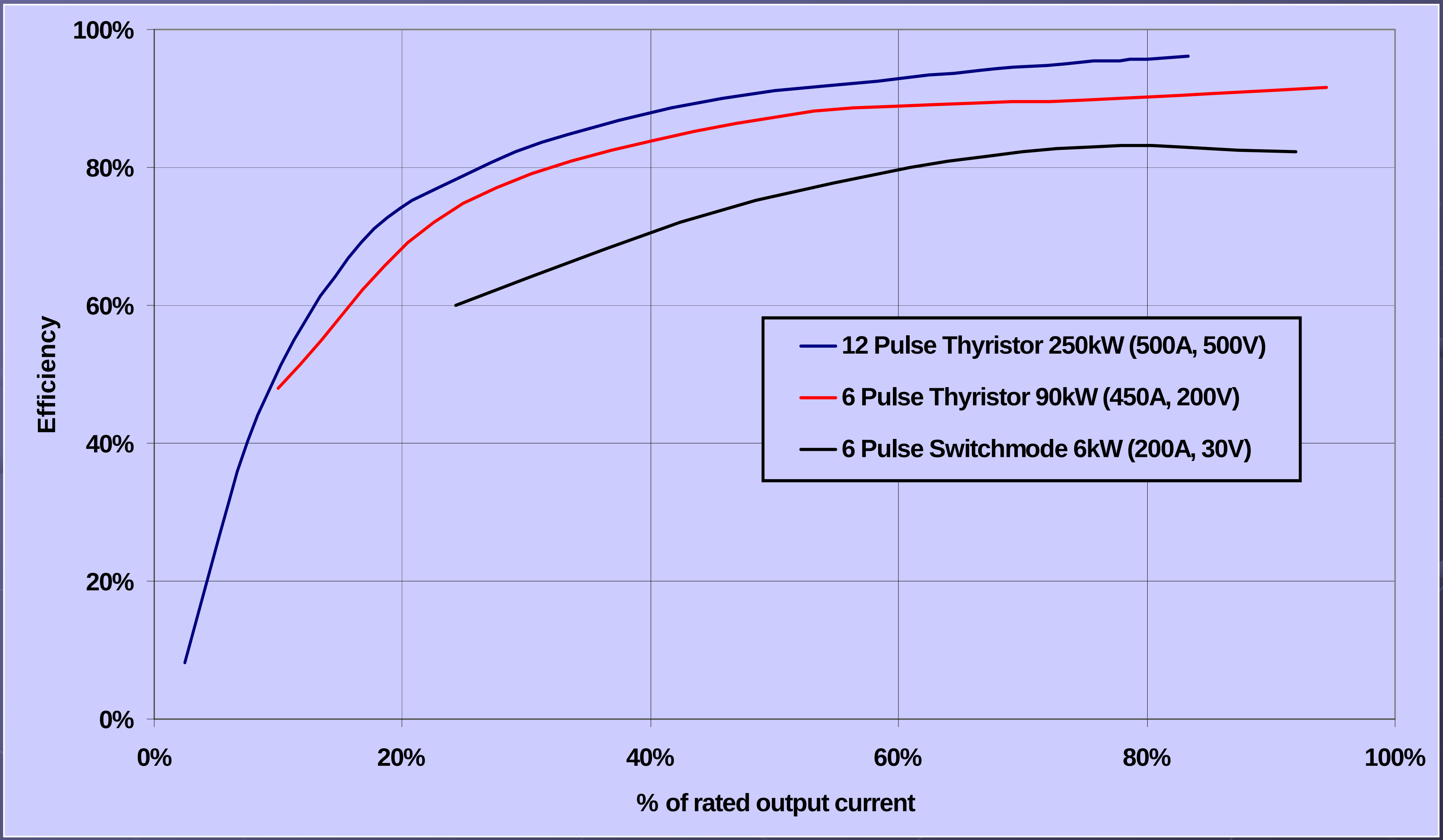


Thermal Image

Linear Efficiency

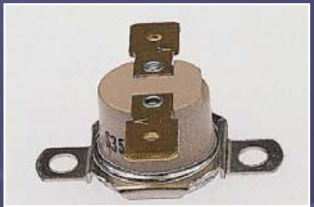


Thyristor Control & Switchmode Efficiency



Natural Air Convection

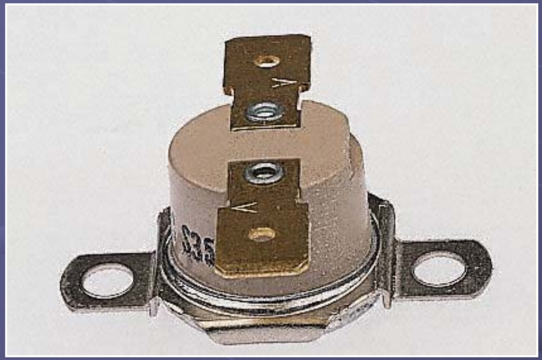
- Protection is provided by bimetallic switching devices.



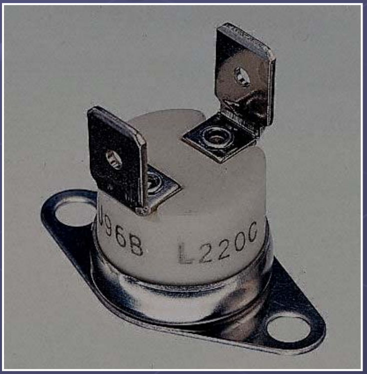
- Generating an interlock when temperature threshold is reached.
- Maximum ambient temperature is 40°C.
- Above this output derates to zero at 70 or 80°C.
- Switches positioned at component hotspots.
- Use manual reset switches when connected in series.

Bimetallic Thermostat

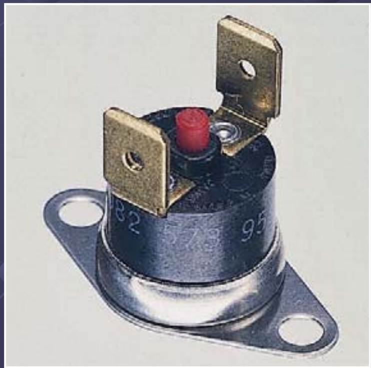
- Thermal switches – simple and commonly used, operate via different expansion rates of the dissimilar metals.
- Multipurpose thermostats – uses bimetal discs, which snap from concave to convex shape giving cleaner make \ break function, can include manual reset.



Basic bimetallic thermostat



High temperature bimetallic thermostat



Manual reset bimetallic thermostat

Forced Air Cooling

- Temperature rise considerably reduced by fans.
- Increased current-carrying capacity for semiconductors.
- Not as efficient as direct water cooling.
- Low power units may require rack mounted fans.
- Surrounding area may require ventilation.
- High speed fans are a source of acoustic noise.
- Airflow detection may be required.

Choosing a Power Converter Fan

Calculate Airflow required:

- Use fan manufacturers recommended formula.
- Find converter losses from efficiency figure.
- Calculate maximum allowable temperature rise.

Chose fan type DC or AC

- Power consumption & cost.
- Monitoring, alarm signals and speed control

Decide Fan direction – normally blow

- Air in laminar, air out turbulent.
- Positive pressure generated inside system
- Reliability – cooler air flowing over fan.

Forced Air Protection

- Manufacturers will only include if specified.
- Types of detection:
  - Micro-switch activated by a vane.
  - Calorimetric principle.
  - Intelligent DC motors can monitor speed of fan.
  - Maintenance program.

Calorimetric airflow sensor / switch

Water Cooling

- Direct cooling is most efficient method of removing heat.
- Reduces volume and weight of converters.
- Low voltages preferred, to minimise leakage currents.
- Demineralised water and insulated water tubes of sufficient length provide necessary impedance.
- Only use stainless steel or copper for metallic pipes.
- Building ventilation can be reduced.

Water Cooling Protection

- Recommended for safe practice to include:
  - Flow meter, installed at the water outlet of the power converter
  - A thermostat near the water outlet, differential temperature can be measured with additional thermostat.

- Cooling water flow measuring devices:
  - Variable area flow meter.
  - Rotor flow switch.
  - Differential pressure flow meter.

Water Flow Measuring Devices

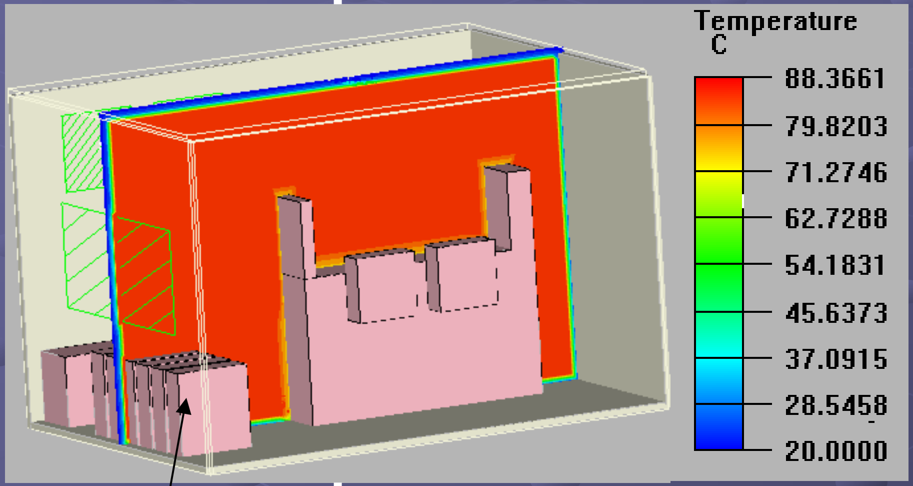
- Uses tube and float system, measures volume flow, magnetic switch, troublesome near high magnetic fields.
- Generates pulsed DC voltages proportional to flow. Cheap, simple and reliable.
- Measures the differential pressure across an orifice plate. Uses orifice plate signal coefficient in calculation of flow rate.

Computational Fluid Dynamics (CFD)

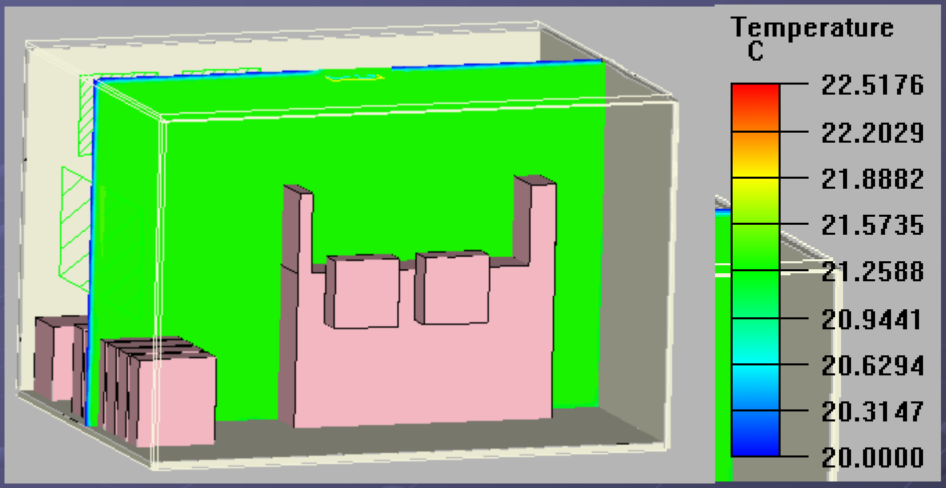
- A tool for compressing the design and development cycle.
- Accuracy of results will depend on the information supplied.
- By identifying the various heat sources, their position, energy dissipation and size, a thermal map of the system can be generated.
- Total surface area of the system and its ambient environment need to be considered.
- The effects of adding cooling can then be explored.

Example of CFD

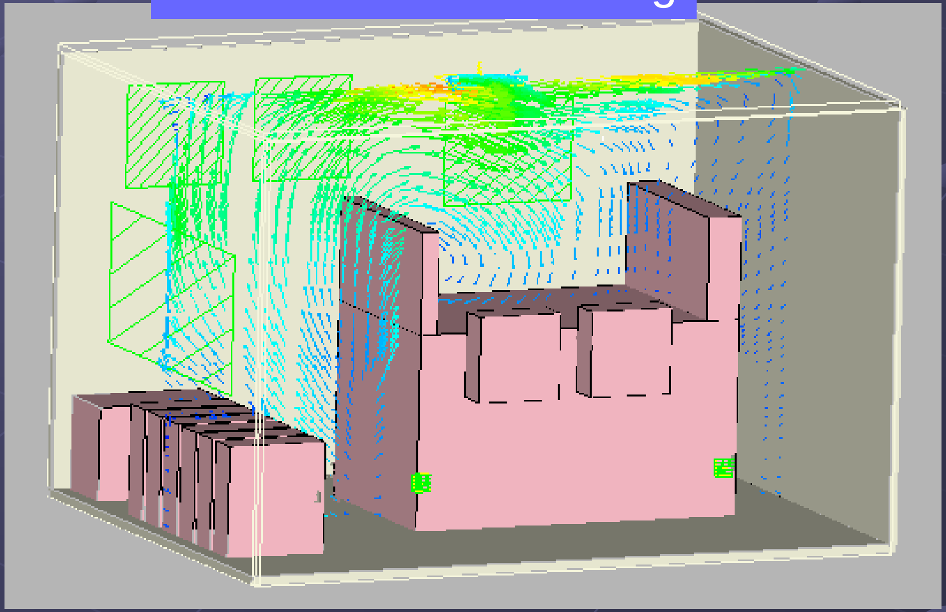
No Cooling



Electrical components affecting airflow



With Forced Air Cooling

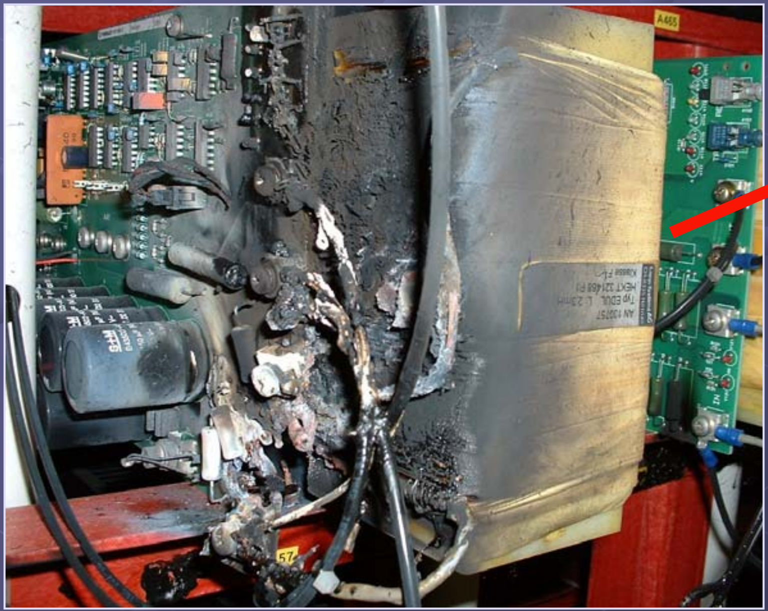


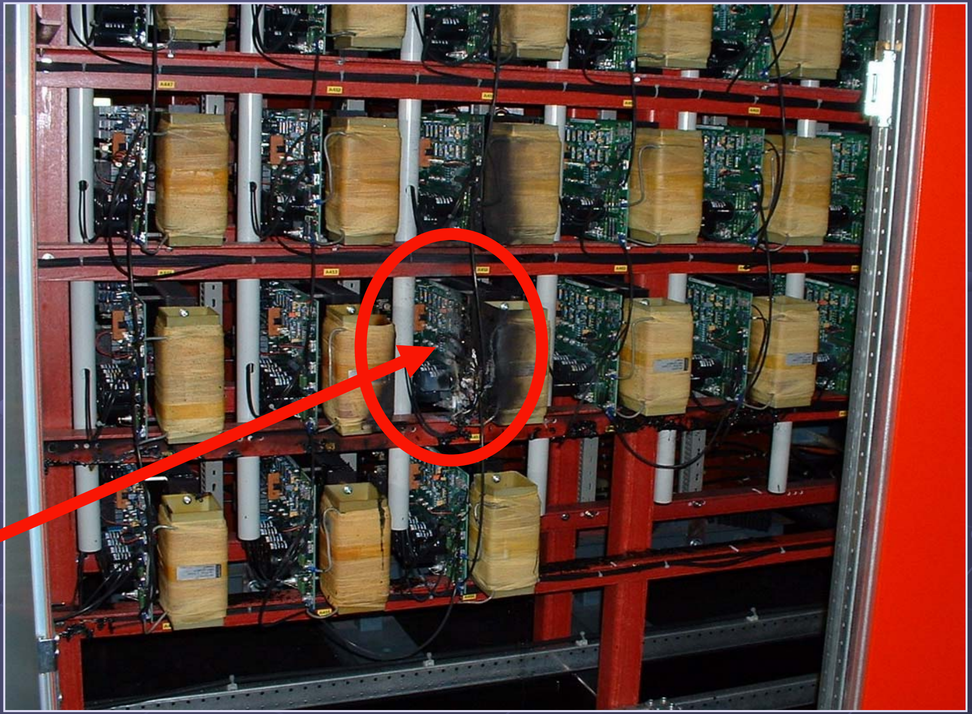
Fire Protection

- If a heat problem is left undetected temperatures can rise to such a degree that there is risk of fire.
- Protection normally supplied by thermocontacts.
- Reducing the probability of fire by:
  - Specifying insulating materials that do not propagate fire such as flame retardant cable.
  - Thermal imaging inspection.
  - Regular maintenance checks.
  - Installing smoke detectors.

Fire Damage

- Thermocontacts can not prevent all causes of fire.
- Such as high resistance connectors or terminations.





HV Converter supplying less than 10 Amps.

AC Supply Protection

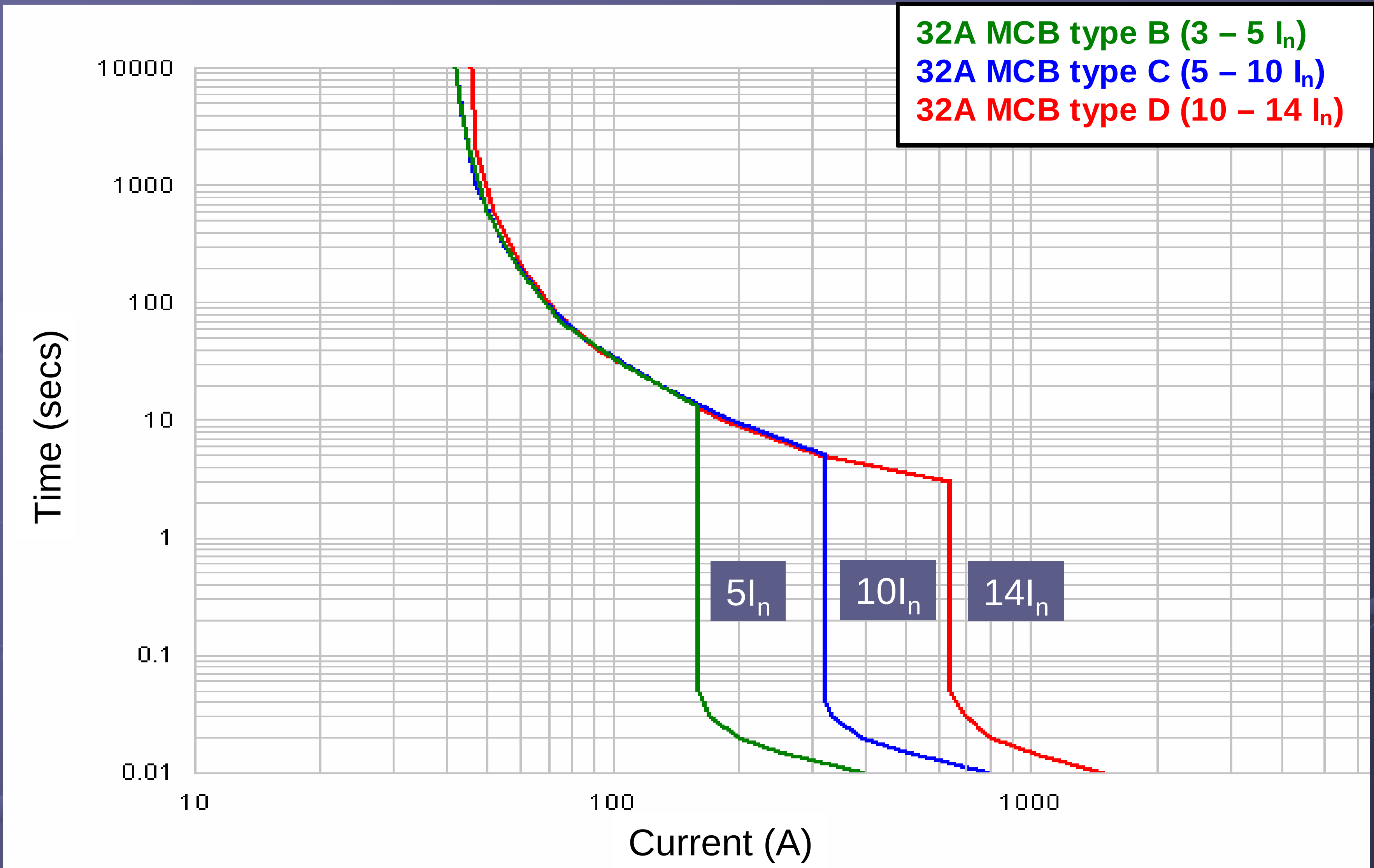
AC Supply Protection

- Level of protection depends on the power converter topology and rating.
- It can consist of some or all of the following:
  - Circuit breaker
  - Transformer interlocks
  - ‘Bucket’ circuits
  - Suppression networks
  - CTs for over-current monitoring
  - Semiconductor fuses

Circuit Breaker

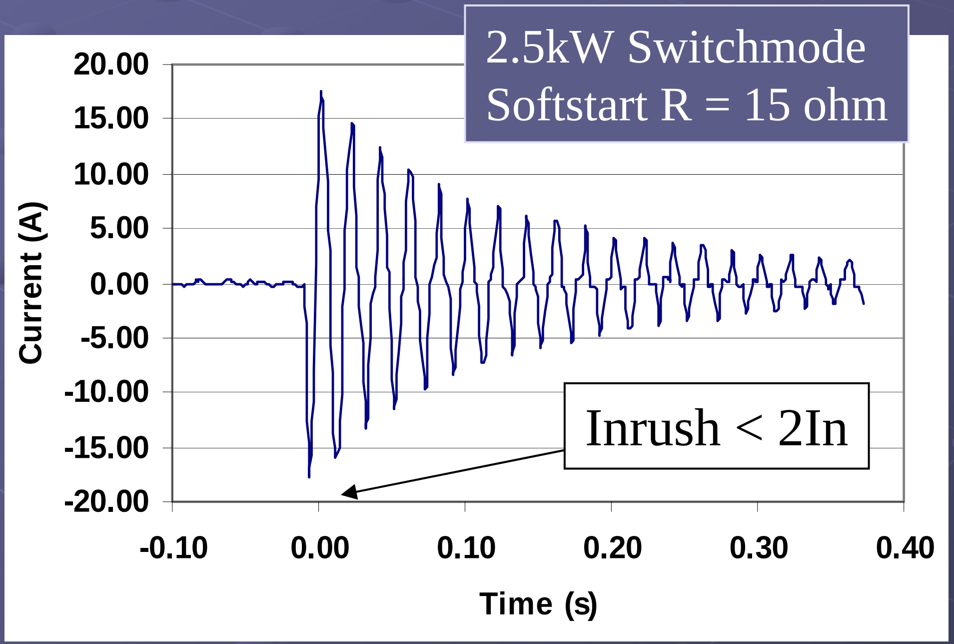
- Disconnects the converter from the supply in the event of an internal fault.
- For high power converters can be used to switch ON and OFF supply.
- Limit number of operations, by inhibiting switching devices.
- Low power application switching performed by the main contactor.
- During switch on, there will be a high current peak (inrush current), which depends on the circuit design and rating.

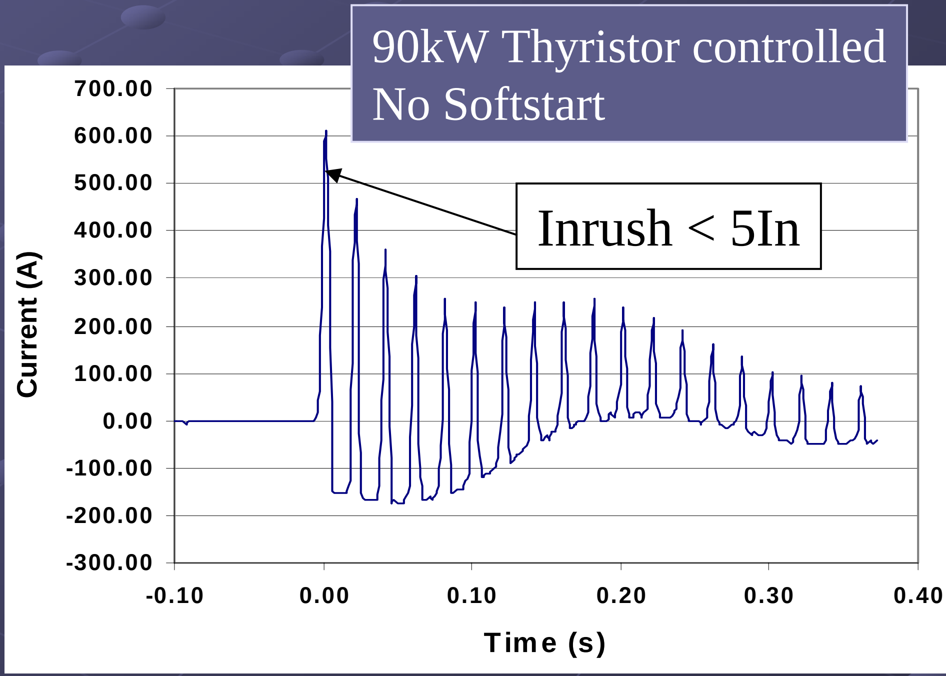
Time-Current Graph – 32A MCB



Inrush Current

- If switchmode employed then the current depends on the input smoothing capacitors.
- In Linear and Thyristor controlled converters the transformer dominates the input response.
- Circuit breaker must be set with a delay before opening to prevent reaction to the current peak.





Inrush Current Suppression

- High inrush current can disturb other users on the network and should be limited by suppression.
- Inrush current peak is normally limited by connecting the converter to the mains via soft start resistors.
- After a delay, the main contactor will short-circuit these resistors connecting the unit to the full mains voltage.
- Protection of the soft start resistor, if the contactor should fail to switch, is provided by a thermal device.
- Resistor must also be capable of supporting several switching cycles per minute.

Power transformer protection

- Converter must accommodate interlocks from external transformers and isolating switchgear.
- Used as warning signals, alerting users of a potential failure, or to trip the converter.
- High harmonics will generate losses due to skin effect in winding.
- Can be designed to withstand short circuits, removing need for semiconductor fuses.
- Most common form of surge suppression is capacitor-resistor network. (‘bucket circuit’)

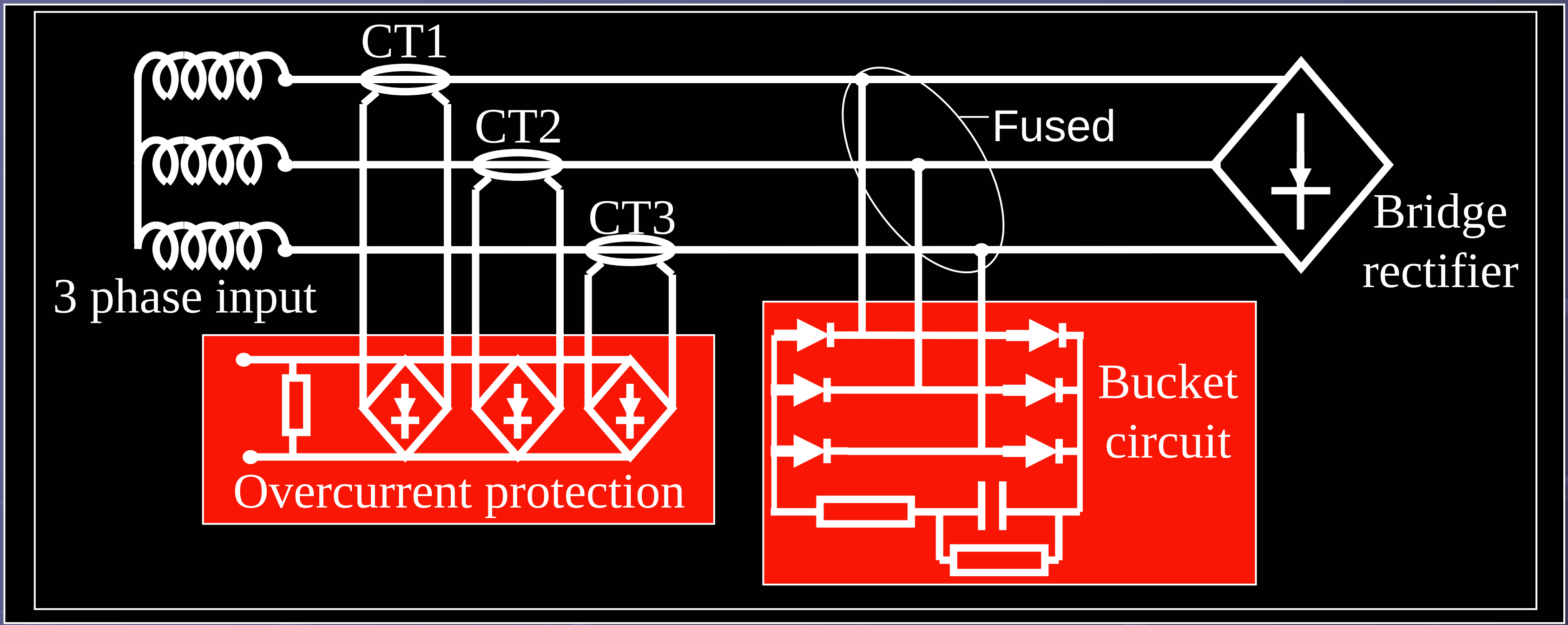
Bucket Circuit

- Connected across the incoming lines to protect the rectifier from high voltage transients.
- Includes discharge and damping resistor.
- Rating will depend on the transformer rating and the stored energy at switch-off.
- Fuses are used to protect the rectifier bridge against short circuit.

Low current rectifier bridge

Reservoir capacitor across DC output

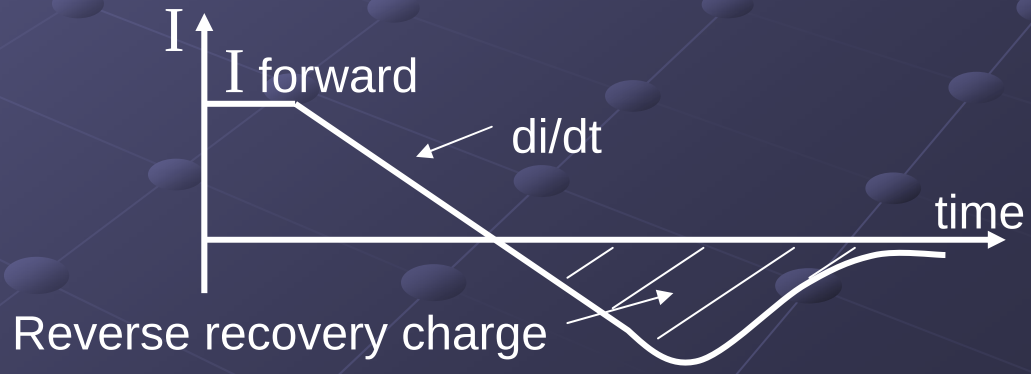
Current Transformers (CTs)



- AC current transformers measure the line current feeding high power converters.
- If 1.2 x In is detected then MCB is opened.
- Electronics are integrated with the converter control system and can be set accurately.

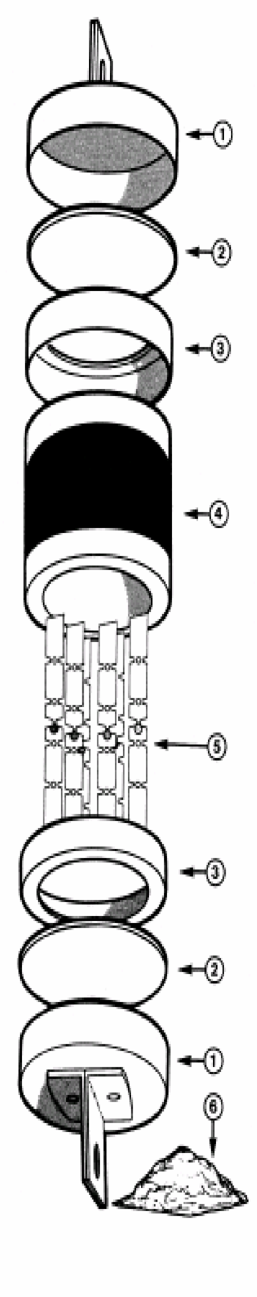
Thyristor Suppression

- Voltage transients are generated at the end of commutation.
- Capacitor-resistor network across each thyristor.
- On thyristor turn-off the current will reverse for a period until storage charge is recovered.
- Storage charge determined by forward current and di/dt rate.
- Storage charge value can be found in thyristor data sheets.



Fuse Links

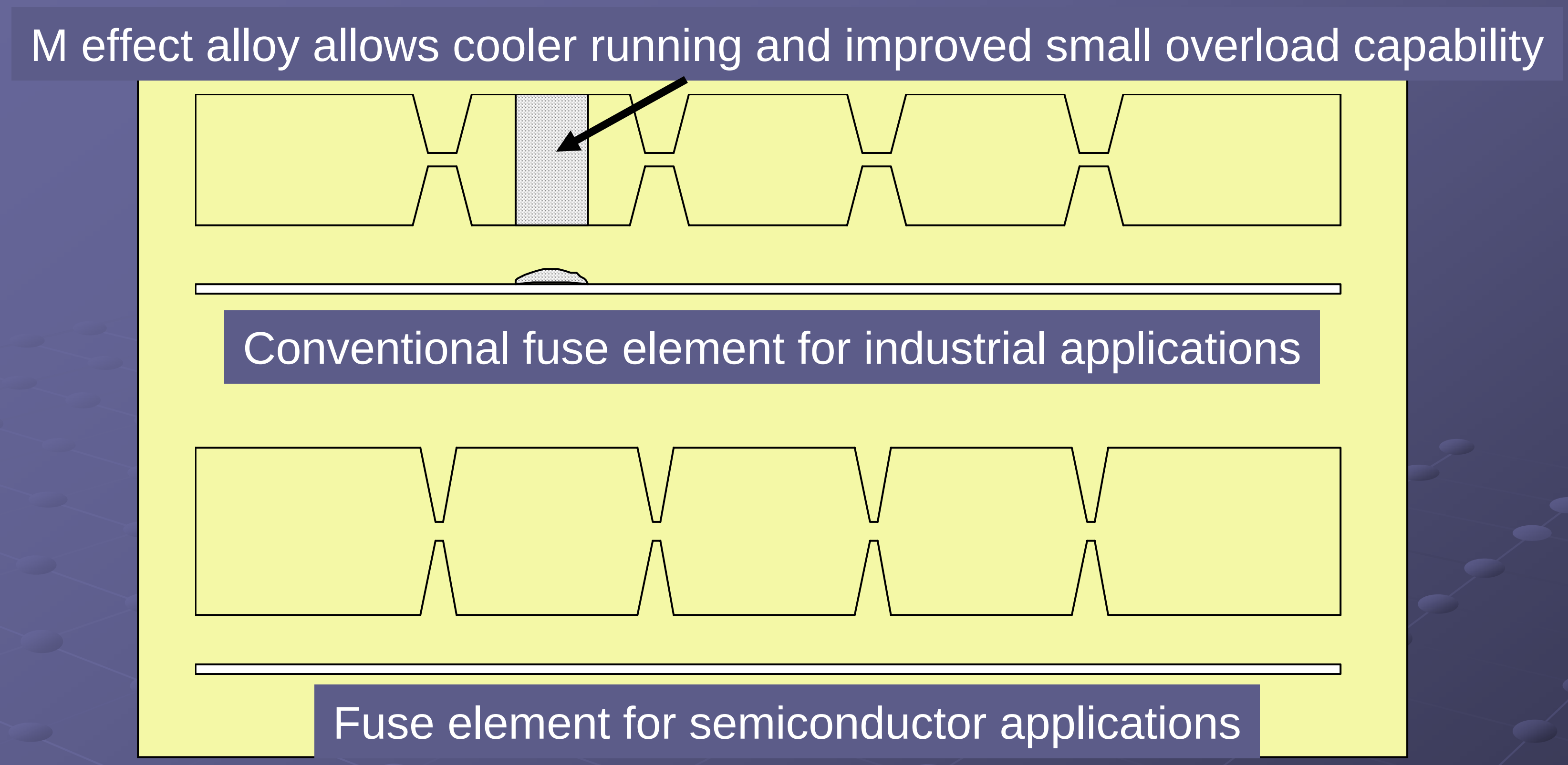
- Element designed to melt and break when the current rises above a certain value.
- Elements are of silver plated copper or silver.
- Special alloy melted onto the elements "M effect" ensures that the fuse link runs cooler.
- Sand filler helps to carry away the heat generated due to the element resistance.
- A graph plotting the operating time of a Fuse Link against fault current is called a Time - Current graph and these are produced according to BS or IEC Standards.



Connector and outer cap
Disc
Inner cap
Body
Fuse elements
Inner cap
Disc
Connector and outer cap
Filler

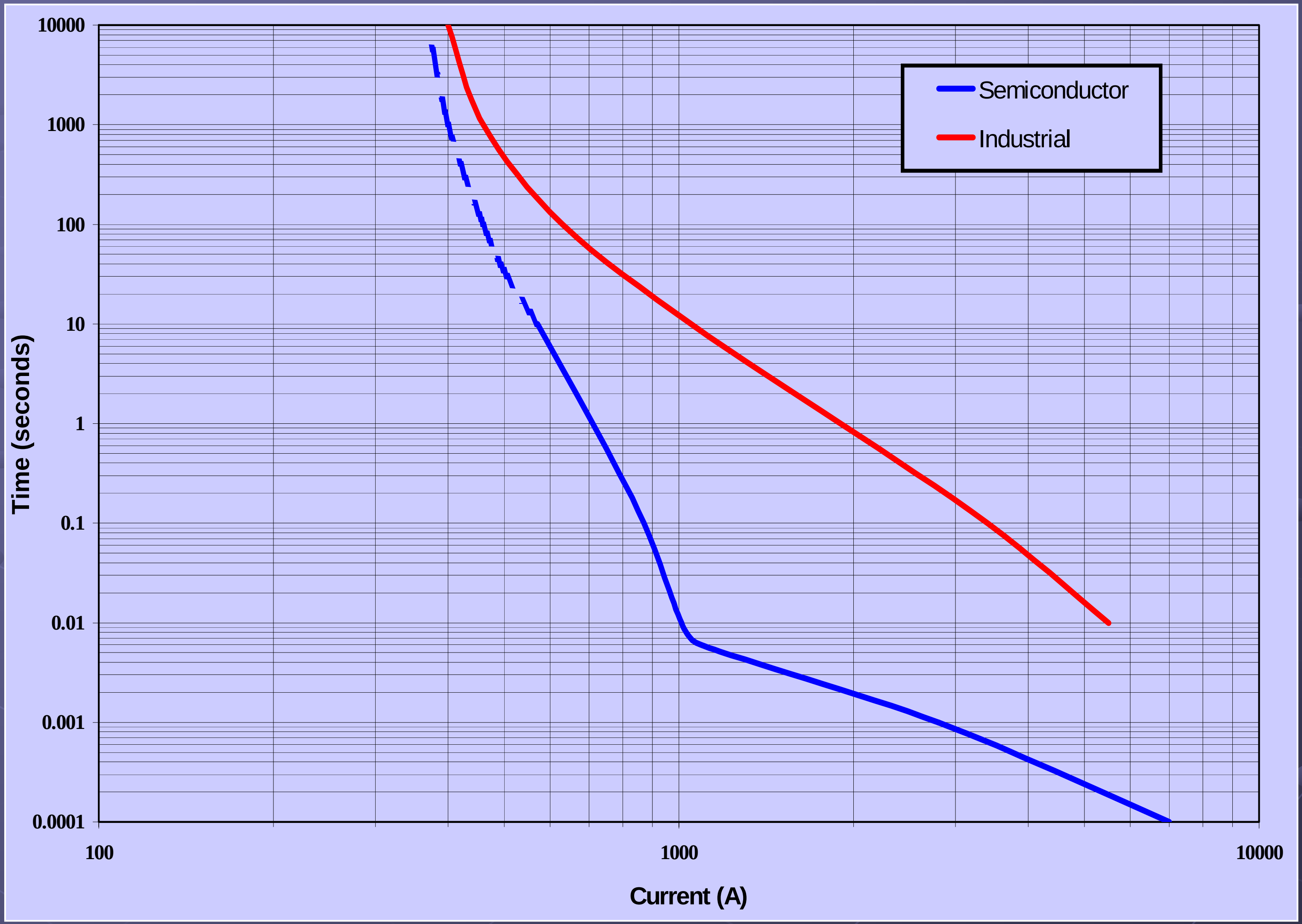
Semiconductor Fuse Links

- A semiconductor is sensitive to excesses in both current and voltage.
- An over-current will damage the wafer thin sections of the device due to over-heating.
- Protected by extremely rapid circuit breaking action coupled with current and energy limitation.
- Fuse links do not depend upon a mechanical system, with inherent inertia.



- A fuse should be selected according to the following criteria:
  - Nominal current of semiconductor to be protected.
  - I^2t of fuse needs to be compared and less than the I^2t of semiconductor.
  - Fuse overvoltage ratings, voltage transients are produced when fuse clears, this should match system overvoltage.

Time-Current Graph - 250A Fuses



Fuse Indication

- Main circuit fuses used for protecting semiconductors incorporate indicators.
- Either positioned at one of the ends or in the central regions of the fuse link body.
- Provide local indication of status of the fuse link.
- May be adapted to operate micro-switches for remote indication.

Summary of Protection Equipment Ratings and Standards

Device	Standards	Current ratings	Short-circuit ratings	Comments
Miniature Circuit Breaker MCB	IEC 898 EN 60898 Household use	1 – 40 A at 30°C	1.5 – 25 kA Typically 6 kA	Thermal & magnetic trip. Type B 3 – 5 x In Type C 5 – 10 x In Type D 10 – 14 x In
Miniature Circuit Breaker MCB	IEC 947-2 EN 60947-2 Industrial use	1 – 125 A at 30°C	1.5 - 15 kA Typically 10 kA	Time delay types available
Moulded Case Circuit Breaker MCCB	IEC 947-2 EN 60947-2 Industrial use	10 – 630 A up to 3200 A	Typically 25 – 150 kA	
Industrial Fuse	EN 60269-1, -2 (BS 88)	2 – 1250A	80 kA	Voltage ranges typically 240 - 690V
Semiconductor fuse	EN 60269-1, -2, -4 (BS 88)	6 – 900A	80 kA	Faster operating time than standard industrial types

Internal Protection

Output Monitors

DCCT

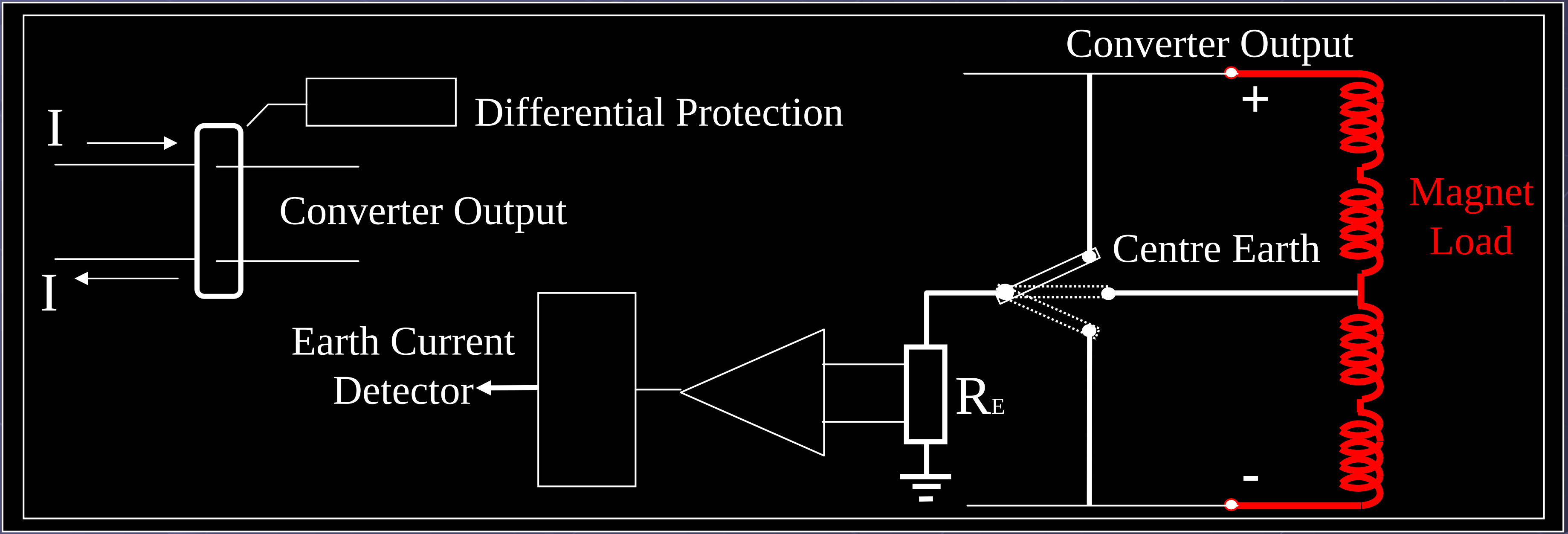
- Output Valid – working within operating range
- Zero current – Used with polarity change over switches and high inductive loads.
- Calibration – incorporate a second DCCT.

Earth Protection

- Isolation provided by mains or HF transformer.
- Load and converter will be referenced to earth at some point.
- Any load failure to earth must be protected by converter.

Earth Protection

- Mid point earth is the preferred solution as max DC voltage is halved.
- Large magnet strings may require several converters, only one is connected to earth the others left floating.
- A low value resistor is normally used for earth current detection.



General Protection

Passive Filter Protection

- Filter chokes have thermocontacts to prevent overheating.
- Filter capacitors and damping resistors have fuses or current transformers to stop excessive AC current.

Series regulation protection

- Transistor failure indication.
- Converter tripped if more than 5% of transistors fail.

DC regulation failure

- Differential error signal too large.

Control

- Auxiliaries supplied from UPS or designed to survive short interruptions.

Freewheel diodes

- Prevents voltage transients and allows magnet energy to discharge.
- Must be rated to operated with continuous nominal current without cooling.

Load Protection

Magnet Interlocks

- Internal earthing protection will be adequate for magnet earth faults.
- Thermocontacts, fixed to the each magnet coil, particularly if parallel water feeds are used, protect the coils against over heating.
- Magnets are normally equipped with a flow meter at the water outlet of the cooling system.
- A clearly visible red emergency push button is mounted on the magnet to enable rapid power converter switch-off.
- Also ensures converters can not be turned on while personnel work on the magnets.

Magnet Safety

- Cables of adequate insulation and cross-section, are used to interconnect the individual magnets.
- Usually the magnets have covers over their busbars. (IP2X classification)
- Safe working procedures are usually adequate to allow personnel to work in the accelerator and beamlines even if the magnets are energised.
- Fitting switches to the busbar covers to activate an interlock if removed provide additional protection.
- Several interlocks of different types (thermal, water flow supervision) is enough to produce a certain redundancy of magnet protection.

Superconducting Magnets

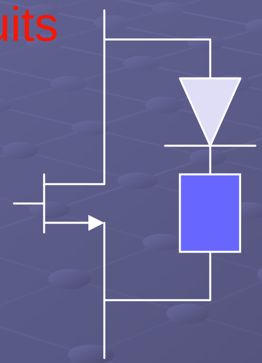
	DL	CERN
Time constants of superconducting magnets, including cables are very long. →	216 Sec	23,000 Sec
Limited voltage is available to prevent over rating the converter. →	10 V	±190 V
		(8 Dipole strings)
To reduce current to zero the only voltage available is in the cables, connectors and last conducting semi-conductors. →	650 A	13,000 A
Controlled discharge rates →	2 A/S	10 A/S

- Discharge circuit must be able to carry this current without any external cooling.

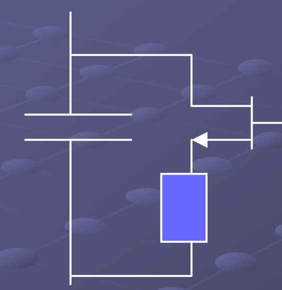
Energy Dissipation

Energy Discharge Circuits

Freewheel Diode



Discharge Circuit



Use LF Output Filter

Return Energy to the Supply

(12p Thyristor)

Magnet Energy

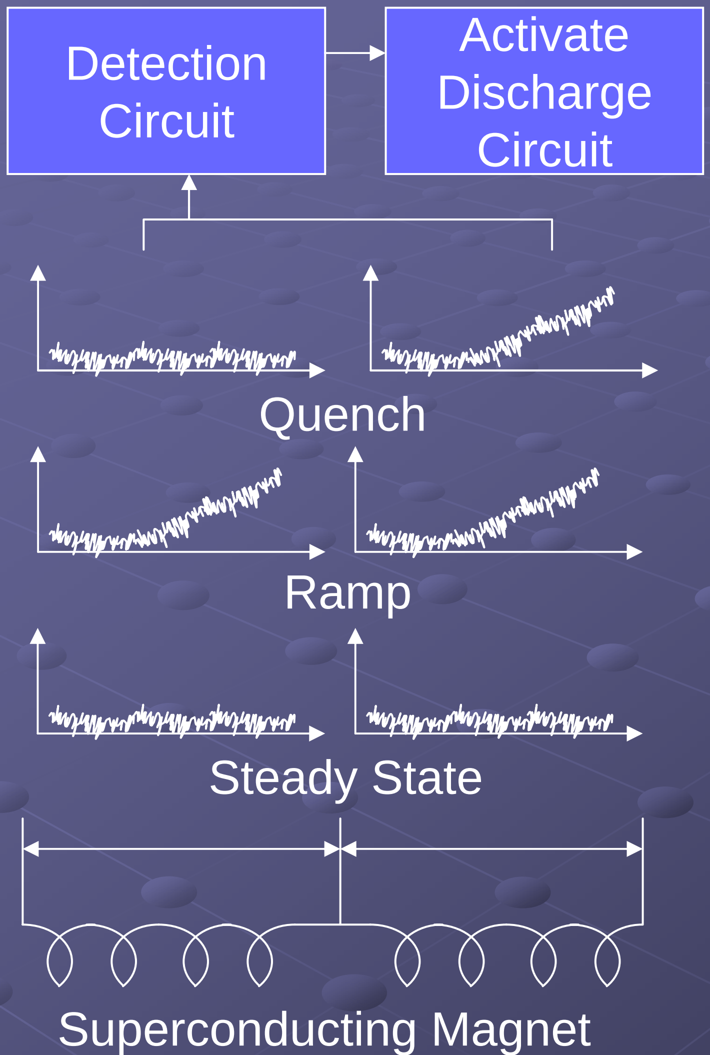
DL – Insertion Device – 250KJ

CERN – Dipoles – 10.4GJ

General Discharge (Refills & Maintenance) → Controlled slow Discharge (Energy recovery)

Quench → Prevent damage & Stress to magnet

Magnet Quench



- Loss of superconductivity in a superconducting magnet is referred to as a ‘quench’.
- A quench detector looks for an asymmetry in the voltage across the coils.
- This activates a fast trip to remove the supply.
- Energy is dissipated in the discharge circuit. (CERN -100 secs)

Crowbar Circuits

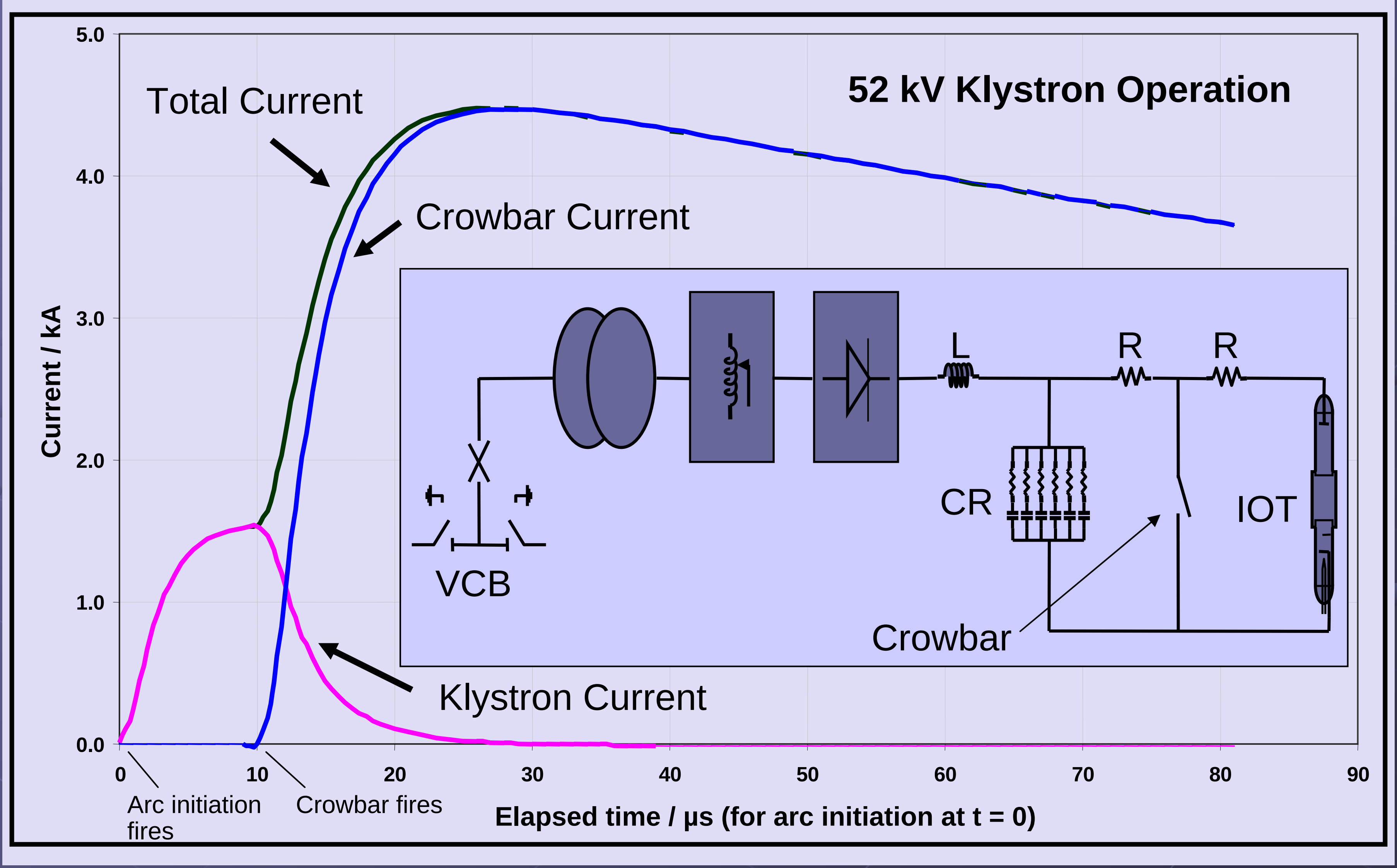
Power Converter Protection

- Active crowbar circuits are used in very high load-inductances.
- Protect the unit from excessive voltages during power converter trips.

Load Protection

- Protect high value equipment in line-commutated converters. Klystron and Inductive Output Tubes (IOT)
- Consist of a high power, high speed switch (or number of switches) capable of diverting stored energy.
- Solid state switches are replacing valve technology.
- Switchmode converters have been developed with low stored energy.

Crowbar Circuits



Diagnostics

Symptoms and Causes

- Cause – a person or event that makes something happen.
- Symptom – a sign, indicating something has occurred.

Typical Power Converter symptoms

Fault Inspection
By engineer or operator

Visual - damage
Smell - burning
Audio - operation
Reduced performance

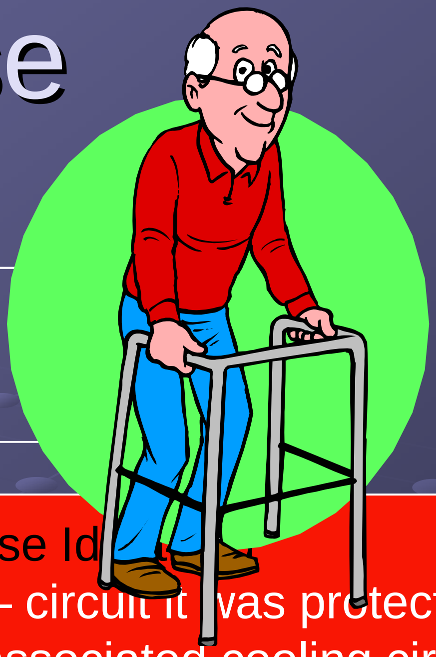
Active Protection
All interlocks & fault protection devices

Ruptured Fuse
Thermal Trip
AC Input Over current
Loss of DC Regulation

Control system latches and records event sequence

Faults are minimised with passive protection, safety factors chosen at design stage

Identifying Cause



Analyse symptoms

Authorised Person
Approved Test Equipment
Safety Procedures

Further Diagnostics
Local Monitoring (test points)
Intelligent processor

Cause Id
Ruptured Fuse – circuit it was protecting
Thermal Trip – associated cooling circuit

Local Monitoring – Technology specific
Trigger circuits
DC Output V & I
AC Input V & I
Ripple current
Earth leakage
Feedback signals

Intelligent Processor – Diagnostic Facility
Event record - AC supply interruptions
Transient monitor DC Output V & I
Responsive to external triggers
Test Modes
Calibration check procedure
Sub-circuit analysis

Diagnostic Summary

- Power converter diagnostics depend on the application, chosen technology and rating.
- Diagnostics should be incorporated at the design stage, any later would be expensive.
- Designer must balance the level of diagnostics against unit replaceability and cost requirements.
- Effective diagnostics will:
  - Minimise accelerator downtime or repair time.
  - Simplify the training for engineers.
  - Reduce Live Working during fault analysis.
- Approved diagnostic equipment must be used that is fit for purpose.
  - Thermal image cameras allow monitoring without contact.
  - Check classification on scopes.

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Questions