

# Protection, interlocks and diagnostics

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## **Abstract**

When designing any power converter it is essential to assess and incorporate adequate protection. The main objective is to offer a solution which is safe, reliable and repairable and that achieves its specification within budget. The level of protection found within each converter varies widely and will depend on the topology employed, its application and rating. This document is a guide to the types of protection engineers should consider mainly when designing power converters, as protection added during construction or after installation will always be expensive.

## **1 Introduction**

Power-converter technology has developed rapidly over the past ten years: Switch-mode converters are now a common feature within particle accelerators, although linear and thyristor-controlled units are still the preferred solution for some applications. The circuit technology may have changed, but many of the traditional protection systems are still incorporated into the modern designs though operating characteristics have been improved with tighter tolerances, faster operating times and/or increased operating ranges.

The main developments have seen the utilization of integrated intelligent processors that provide power-converter users with self-diagnostic facilities. The power-converter engineer must not only design units with improved performance, but also with higher reliability and minimum repair time.

As power-converter ratings range from a few hundred watts to several megawatts, it is difficult to establish general rules for their protection. The field of power-converter protection is extensive and depends on a number of factors; it is not possible to consider specific applications here. The generic topics of personnel safety, thermal management, operational issues and diagnostics are reviewed, but should only be used as a basic guide to the types of protection currently available and how to apply them to system designs.

## **2 Personnel protection**

### **2.1 Safety legislation**

More important than protecting the equipment is ensuring the safety of personnel who work on or near the power converters. The rules governing the construction of power converters are the same as those for other electrical equipment and need to be considered at the design stage.

When producing electrical equipment or systems for use within the European Union, conformity with the *Low Voltage Directive* (LVD) is mandatory. This covers the supply voltage ranges from 50 V to 1000 V ac r.m.s. or 75 V to 1500 V dc. To show compliance with LVD, manufacturers need to demonstrate that their equipment is designed, built, and tested to the appropriate standards.

At present there is no dedicated safety standard for power converters. However, for electrical equipment there are useful reference standards which can be specified, such as IEC 60950, *Safety of Information Technology Equipment* (intended for IT equipment but covers power electronics) and BS EN 60204, *Electrical Safety of Machines*.

Electrical equipment is considered safe if no accidental contact with any live or potentially live components can be made. This is achieved by installing converters in metal enclosures that are earthed and by guarding the input and output connectors with appropriate covers. If the enclosure is opened, the input supply must be disconnected to prevent exposure to live conductors. This can be achieved with micro-switches or specialist key arrangements that force personnel to isolate and earth equipment before keys are released to enable access. If the equipment contains energy-storage devices, timers should be fitted to allow discharge before entering, at which time resistive earthing sticks (rated to withstand the energy transfer) should be placed on potentially live equipment. Earthing sticks are a secondary protection and are used to prove the system is dead before work commences; they should not be used as the primary means of energy discharge.

If the equipment is too large to fit into an enclosure, then a separate fenced area will be needed with similar protection. Access will be limited to skilled, instructed personnel only.

## 2.2 Safe working practices

Each accelerator should have its own set of safety procedures, listing the control measures to minimize the risks associated with all identified hazards. Typical general electrical precautions that have to be taken when working with electrical equipment are as follows.

- Isolate the equipment from all sources of supply (multiple inputs are frequent in converters for accelerator applications).
- Prevent unauthorized connection or operation by fixing safety locks and caution notices at all points of isolation. Fix visible electrical warning signs on adjacent live equipment.
- Discharge the installation and, if power capacitors are installed in the equipment, close the discharge switch.
- Where practicable, prove dead with a voltage test indicator at all points of isolation and at the places of work.
- Where practicable, earth the incoming terminals.
- Never work alone.

Access to accelerator equipment buildings is often limited when the magnet loads are energized. This is the case when the magnetic fields are very high, when the zone is exposed to radiation during accelerator operation, or when the busbars of the magnets are not protected. To ensure personnel protection, access is allowed only when the power converters are turned off. This interlock system is usually integrated into a more complex general access system, which includes the condition that all power converters be turned off before giving access to the zone.

## 2.3 Live working

It is known that at some stage during the life of equipment live working may be necessary. Therefore, appropriate action should be taken to minimize the risk. This can be taken at the design stage, the time when the equipment is selected, the installation stage, or at all three stages. At the design stage, consideration should be given to segregating parts that may require work and so provide protection from adjacent parts which may be live. By designing equipment with effective diagnostics and

protection, live working should be reduced. If live working is required, sufficient space and lighting levels are critical.

A typical regulation may state that “no person shall be engaged in any work on or near any conductor (other than one suitably covered with insulating material so as to prevent danger) that danger may arise unless

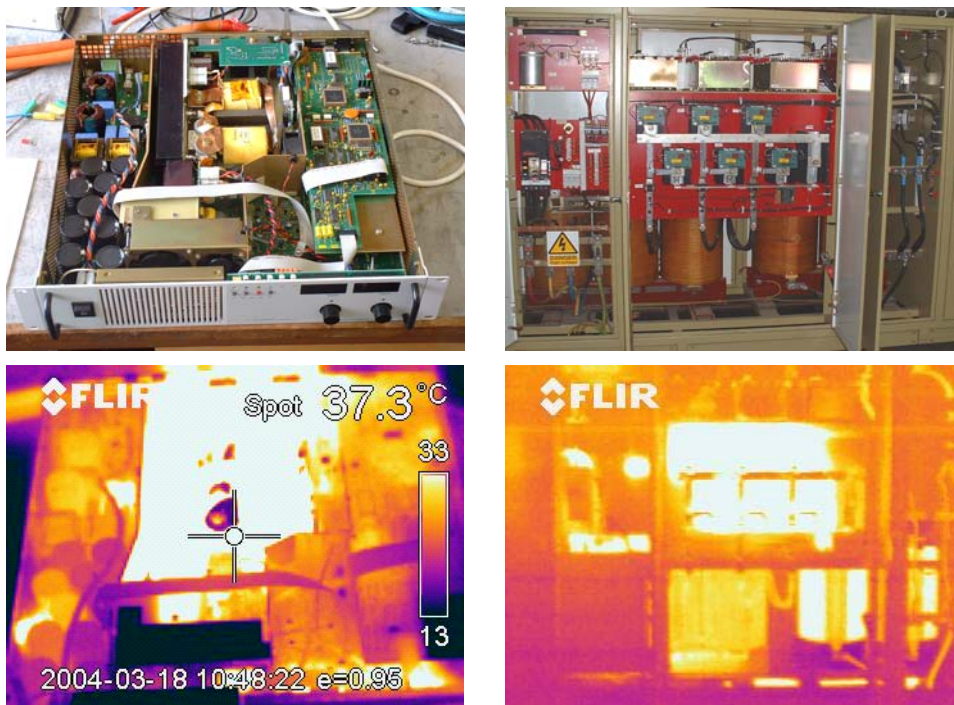
- it is unreasonable in all circumstances for the conductor to be dead and
- it is reasonable in all circumstances for the person to be at work on or near the conductor while it is live and
- suitable precautions (including where necessary the provision of suitable protective equipment) are taken to prevent injury.”

These statements are intended to discourage live working and to ensure that the engineer responsible has considered all other solutions before live working is employed.

### 3 Thermal management

#### 3.1 Design considerations

The basic function of a power converter is to transform the incoming three-phase or single-phase current into a dc or pulsed current and thus satisfy the specification produced by the magnet designers and the accelerator physicists. The flow of energy is normally from the ac supply to the load, but sometimes in pulsed or superconducting applications the energy stored in the magnet returns to the ac supply via the power converter. The energy passing through the converter will produce losses and these losses will create heat. This heat is not evenly distributed within the power converter; therefore careful thermal management is required where the losses are concentrated.



**Fig. 1:** Switch-mode (left) and thyristor (right) power-converter thermal images

To manage these losses, the power-converter designer must consider component layout and cooling method, ensuring heat is removed from the unit and the surrounding area. All elements that carry current will produce heat. The magnetic elements in the circuit also have iron losses induced by the varying magnetic field, and elements protecting the converter against over-voltage have losses in the RC networks.

It is reported that excessive temperature accounts for 55% of all electronic equipment failure, but through effective thermal management planning early in the equipment design, nearly all of these failures could be avoided. The main cause of overheating is a result of the ongoing drive towards miniaturization.

In modern accelerators the quadrupole and sextupole magnets are often powered individually, giving optimum versatility in adjusting the lattice functions in the insertion regions. This has influenced the philosophy of power-converter design, with increased demand for compact, low-power modules. In higher-power applications these modules are made versatile, enabling connection in a series and/or parallel configuration. In general, the dipole magnets are still connected in series and will require only a single, high-power current converter.

It became an accelerator standard to house these large power converters in separate plant room(s) with a dedicated ac distribution and ventilation system. Recent developments have meant an increase in localized instrumentation areas that contain large numbers of low-power modules. The voltage drop in cables from the local instrumentation areas or plant rooms to each magnet have non-negligible effects. The access arrangements (labyrinths) into the accelerator tunnel and the cable cross-sectional area determine both the voltage drop and the power loss in each cable. These calculations should be considered when assessing both the loading on the heat management systems for the local instrumentation areas and the output voltage ratings of the power converters.

All the heat produced by the converters and cables will be extracted by air or by water. If air cooling is employed the building has to be designed accordingly, ideally with a false floor and an adequate ventilation system. The level of temperature control for a building will depend on the climate and the power-converter specification. If temperature stability can be maintained, this will reduce the day and night variations in converter currents. In extreme temperatures, it may be necessary to introduce heat exchangers or to refrigerate the incoming air to an acceptable level. In new buildings, a dedicated ventilation system should always be installed.

### **3.1.1** *Natural air cooling*

Adequate protection for natural air convection equipment can be provided by bimetallic switching devices, which are located on specific elements to provide an interlock when a temperature threshold is reached. In general, power-converter components are specified to work with a maximum ambient temperature of 40°C; above this the power-converter output derates linearly to zero at 70°C or 80°C. These switching devices fall into three main subsets.

- Thermal switches are the simplest and most commonly used and operate with a bimetal strip positioned between two switch contacts. When heated, the strip bows due to the different expansion rates of the dissimilar metals. They are current limited by contact size and offer narrow operating bands.
- Multipurpose thermostats use bimetal discs, which snap from a concave to a convex shape. They allow wider switching points and a cleaner make/break function. They can include a manual reset, but still have a large dead band due to the hysteresis of the material used.
- Precision thermostats work on the same principle as the multipurpose type, but allow tighter control with a reduced dead band.

These switches are placed at the hottest spot on the device to be protected. For semiconductors it is convenient to place several switches on different cooling fins in case cooling ducts become blocked or individual IGBTs or thyristors take more current than others (perhaps due to missing firing pulses, imbalance of current in parallel connected devices). If several thermo-contacts are connected in series, contacts should be equipped with indicators (resettable) to identify the element that has tripped.

If it is not possible to extract the heat by convection, forced air cooling may be required.

### **3.1.2 Forced air cooling**

The temperature rise in a piece of equipment can be considerably reduced by fans, which make it possible to increase the current-carrying capacity of semiconductors, thus aiding the drive towards smaller power converters.

When using forced air cooling, it is obvious that anything which restricts the movement of air within the system (electronic cards, cabling, switching devices, blocked air filters etc.) affects the pressure gradient between the inside and outside of the cabinet. As fan performance figures are usually based on freely ventilated systems, it is easy to overlook the potentially disastrous effect of mechanical restrictions on system cooling and to under-specify the cooling requirements.

The power-converter designer, after calculating airflow, must choose between a dc- or ac-powered fan. A dc fan will generally consume less power than the equivalent ac fan, while offering the ability to monitor status and alarm. It is easier to control speed, offering a much more flexible cooling option. There is a slight price penalty for using dc fans, and in general ac fans are still widely used.

For most applications the choice is to push air into a system. This is because the air going into a fan is laminar, whereas the air exiting it is turbulent and as such it is much more effective at cooling. Indeed with laminar airflow, hot spots can occur. When air is forced into an enclosure it creates a positive pressure within the system. This helps avoid airborne dust particles being drawn into the enclosure. To benefit from this it is necessary to employ filtration, otherwise dust will be 'pushed' into the enclosure. This means that seals around doors and gaps in the equipment housing are not quite so critical. Yet another benefit is that the life of the fan is heavily dependent upon the temperature of the air flowing across its motor. Fitted on the input side, it is bathed in cooler air than it would be if used to extract hot air from the enclosure.

A forced ventilation system will require not only internal power-converter fans, but also external fans to ensure hot air removal from, and circulation within any external mounting system (e.g., rack mounted). If the surrounding warm air is evacuated by an air-conditioning system that is cooled by chilled water, the water temperature needs to be regulated accurately; however, it is only providing secondary cooling, unlike direct water cooling.

If closed-control air conditioning is installed, it is important that the load be kept as constant as possible. If the power converters are turned on and off or ramped, this may cause room-temperature instabilities. The initial start-up after a shutdown could cause fluctuations in the heat loading and may need some settling time.

High-speed ventilators are also a source of acoustic noise. Low-speed ventilators are more reliable and less noisy, but with reduced speed comes reduced cooling efficiency. When forced ventilation is used, adequate protection of the fan motor is required. Airflow detectors are often employed, comprising either a flap with a microswitch or calorimetric airflow sensor/switch (heated temperature-dependent resistor). When using intelligent dc fans, their speed-proportional commutation pulses can be monitored by an external circuit and if they slow down or fail a warning or trip signal can be operated. The power-converter designer chooses whether to include monitoring or to

simply rely on a maintenance plan. In general, converter manufacturers will not include airflow protection unless specified.

As an alternative to forced air cooling, normally when the designer has space restrictions, water cooling is an efficient and popular solution.

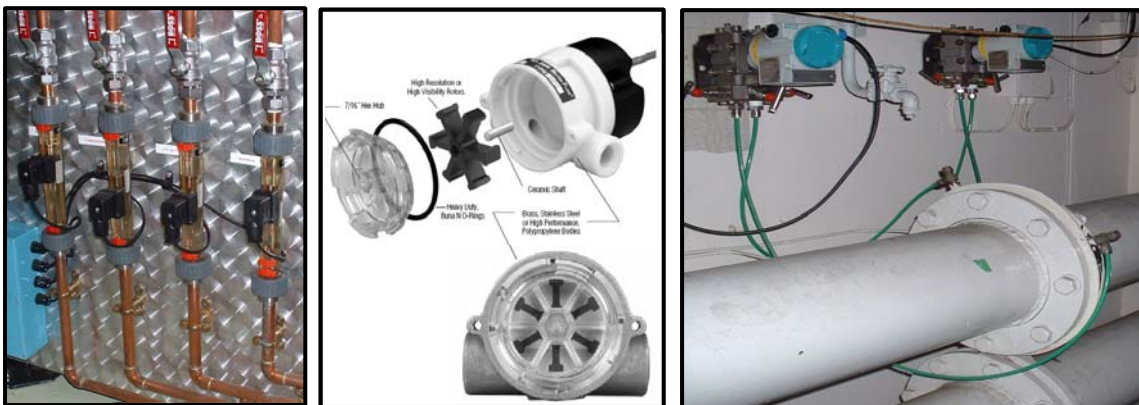
### 3.1.3 Water cooling

If water cooling is used, the designer will normally favour a high-current, low-voltage solution. Electrical insulation has to be assured by the use of demineralized water and by insulated water-pipes of sufficient length to give the necessary impedance. The pipe internal diameter must be large enough to avoid blockages. Reduction valves can be fitted to prevent over-pressure and filters may also be required. The temperature of the complete water system has to be kept above the dew-point level in order to avoid condensation on the outside of the pipe-work. If the power converters are in a room where the temperature can fall below 0°C, there must be a facility to drain the water system.

The preferred design is a separate, closed, demineralized water system with a heat exchanger. This type of system is only practical for a large quantity of small power converters or a single power converter of several megawatts rating. The demineralized water will limit the leakage current and prevent erosion of the metallic parts of the water circuits, but only stainless steel and copper (no brass) can be used. A temperature regulator will hold the water above the dew-point level.

Direct water cooling is the most economical method of removing heat from power electronics, and has the benefit of reducing the volume and weight of power converters compared with an equivalent air-cooled system. The amount of ventilation in a building can be reduced, since the majority of the heat loss by the power converter is evacuated by the water. The heat generated by chokes, control electronics and passive components will still normally require air cooling. The risk of mixing electronics and water can be minimized by eliminating joints within the power converter and by compartmentalizing the power electronic components. It is recommended for safe practice to include the following interlocks.

- A flow meter, with a normally open contact that closes once an adequate flow is reached, installed at the water outlet of the power converter. Operating delays are often incorporated to prevent spurious trips (often due to air pockets).
- A thermostat near the water outlet to measure the differential temperature to detect water overheating and power-converter efficiency.



**Fig. 2:** Various water flow measuring devices

The following are the most commonly used devices for measuring the flow of cooling water for converter operations.

- Variable-area flow meter—uses tube and float system, measures volume flow, but utilizes a magnetic switch and can be troublesome near high magnetic fields.
- Paddle flow switch—generates pulsed dc voltages proportional to flow. Cheap, simple and reliable.
- Differential-pressure flow meter—measures differential pressure across an orifice plate, provides an analog output for triggering external interlocks.

### 3.1.4 Efficiency

Power-converter losses depend on the application and topology employed. There is a variety of power-converter designs available, but for simplicity they can be categorized into the following groups.

- *Linear*—The main losses will be concentrated at the series regulator. As the efficiency of linear converters is low, they are mainly used for low-power applications less than 5 kW, where space is not restricted and high stability better than 1 ppm or low ripple is required.
- *Thyristor controlled*—These regulate the current by controlling the firing angle of a thyristor; they give high efficiency, at the expense of a poor power factor. The losses in this topology are concentrated in the thyristors and magnetic elements. They are mainly used for high-power applications and can be adapted to match various load impedances.
- *Switch-mode*—These designs are thermally challenging, as the objective is to contain the power converter within a small volume. The majority of losses occur at the HF switching element. For the medium- and low-power range, switch-mode converters have high efficiency and a good power factor.

The resultant losses depend on the topology used and the percentage of output current set during operation. It is not safe to assume that the converter’s efficiency is the same over the entire operating range; often suppliers will only specify the full load figures. The best efficiency is by matching the nominal load to the rating of the power converter. An accurate assessment of the heat loading can result in major cost savings in the air-conditioning system.

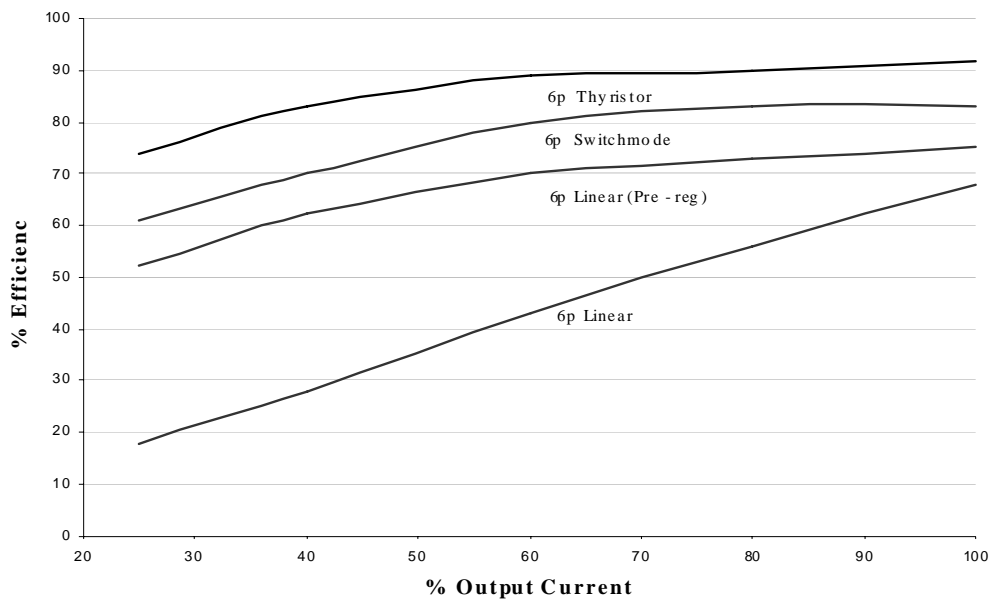


Fig. 3: Various six-pulse (6p) power-converter efficiency measurements

### 3.1.5 Thermal management software

There are various software packages available to help design the optimum cooling system. By identifying the various heat sources (switching devices and magnetic elements) by position, energy dissipation and size, a thermal map of the system can be generated. Any hot spots or high enclosure temperatures found can be reduced by adding the effects of water or forced air cooling. Any equipment that restricts airflow must be included in the simulation as this affects the efficiency of the forced air cooling.

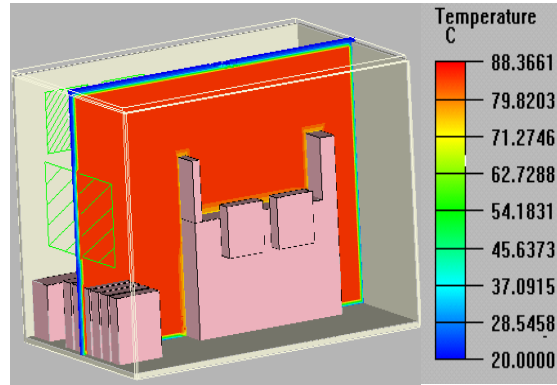


Fig. 4: Simulated temperature cross-section

The total surface area of each module and its surrounding environment needs to be considered. Computational fluid dynamics (CFD) is a tool for aiding the design and development process, but the accuracy of its results will depend on the information supplied.

After the power converter is manufactured a thermal imaging camera can be used to verify the simulated results. It can also be used as a diagnostic tool for analysing overheating problems within electronic equipment.

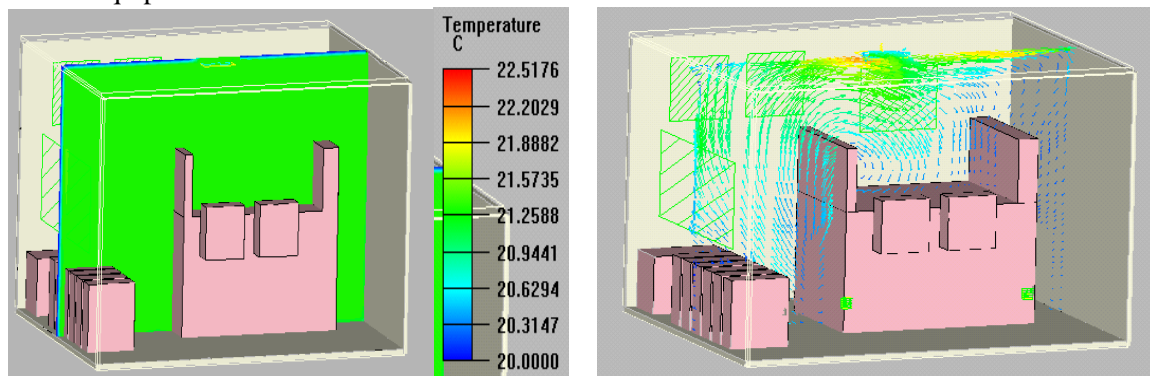


Fig. 5: Simulation after applying forced-air cooling

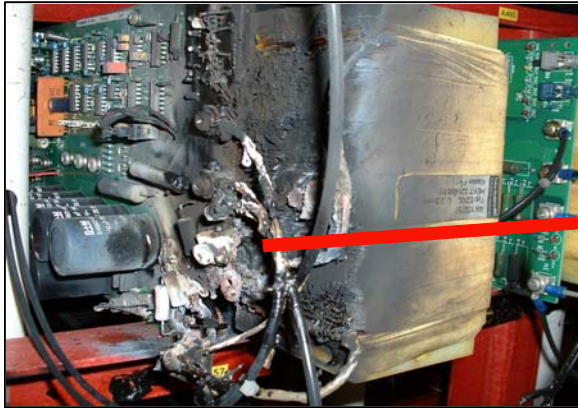
### 3.1.6 Fire protection

Hot spots can appear within power converters and are concentrated at the devices with the most losses, especially when forced ventilation is used. If these are left undetected, their temperature can rise to such a degree that there is a risk of fire as discussed previously. The normal way to prevent excessive temperatures is to install thermo-contacts that provide interlocks to the power converter. This form of protection is not adequate to detect causes of fire such as high-resistance connectors or terminations, particularly in high-current applications.

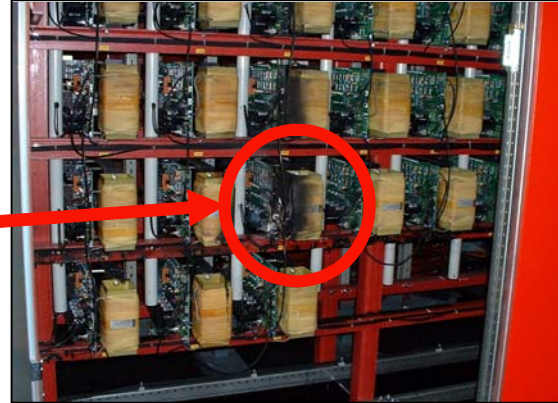


Figures 6 and 7 show a switch-mode power converter after a fire. The converter has been operating for 18 months, supplying a dc current of less than 10 A, the fire initiated from a connector with a high resistance. Careful inspection of converters with a thermal imaging camera and then regular maintenance checks would reduce the probability of such an occurrence. Since the incident, the unit has been fitted with a smoke detector.

To minimize damage during fires, converters should be specified with insulating materials that do not propagate fire, such as flame-retardant cable.



**Fig. 6:** Fire-damaged switch-mode module



**Fig. 7:** High-voltage switch-mode converter after fire

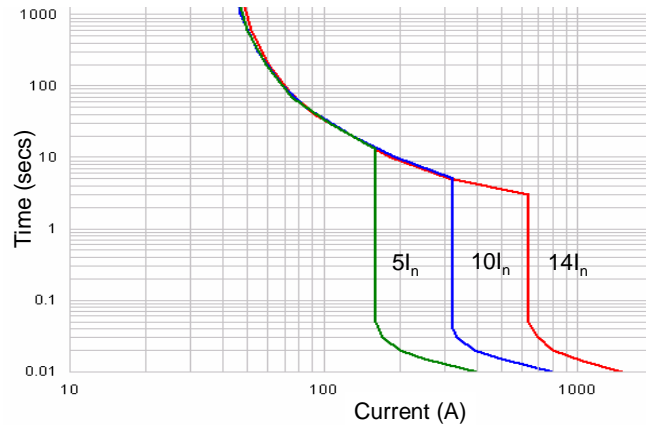
## 4 ac supply protection

The level of protection necessary for the ac supply will depend on the power-converter topology and its rating. It can consist of single-phase, miniature circuit breakers (MCB) or a complex arrangement of semiconductor fuses, transformer interlocks, surge protection ('bucket' circuits), suppression networks and current transformers (CTs) for over-current monitoring.

### 4.1 Miniature circuit breaker

The prime function of the MCB is to disconnect the converter from the supply in the event of an internal fault, irrespective of the short-circuit capacity of the source. On high-power units the MCB could also perform the task of switching on and off the supply, but because of its limited number of operations (about 10 000 at no load) it is not ideal. To improve reliability, operation of the MCB is limited to interlock trips and isolation requests; the output in normal operation is inhibited by clamping the switching semiconductor device. On low-power applications the tasks of switching and protection are separate, with switching performed by a contactor on the ac supply. In fact, most modern switch-mode units offer a function that can inhibit the switching semiconductor device.

During switch on, there will be a high current peak (inrush current), which depends on the circuit design and rating. In linear and thyristor-controlled power converters the transformer will dominate the input response. The current is determined by the transformer construction, especially the short-circuit impedance, applied voltage and the allowed iron losses, line impedances and the timing of switch on with respect to the mains voltage cycle. The amplitude of the current peak will normally decay to half its value after 10 to 20 periods.



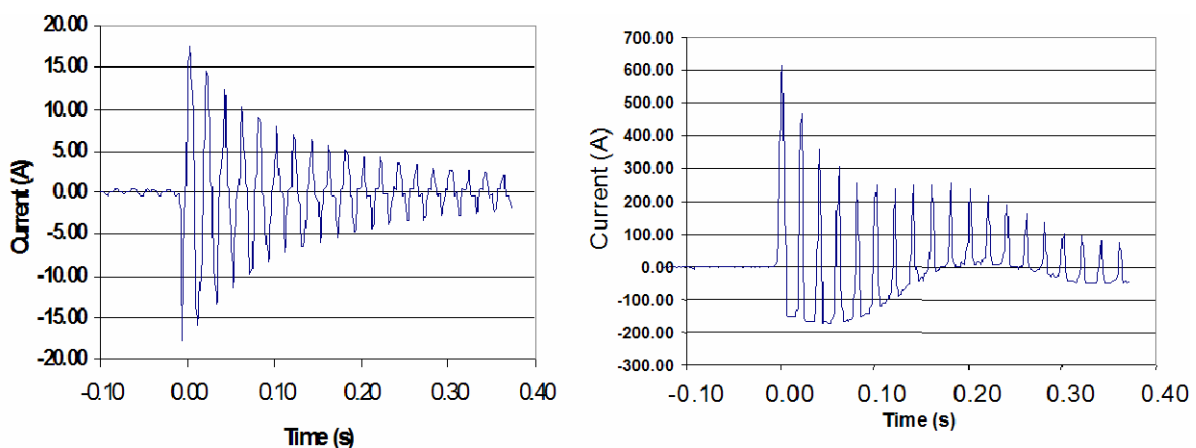
**Fig. 8:** Time–current graph for a 32 A miniature circuit breaker ( $I_n$  = nominal current)

For higher power ratings the decay will be slower. The MCB must be set with a delay before opening to prevent reaction to the current peak. This high inrush current can disturb other users on the power network and should be limited with suppression.

If switch-mode converters are employed then the inrush current depends on the input smoothing capacitors, line impedances and the timing of switch on with respect to the mains voltage cycle. If a large number of low-power modules are installed, then turn-on discrimination can be used to minimize power network disruption.

#### 4.2 Inrush current suppression

The 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 directly to the full mains voltage. The selection of the soft-start resistor and its power rating can be determined by assuming the power converter input impedance is zero and the current is limited by the resistor and line impedance only. As a guide the current should be limited to less than five times the nominal current with a closing time delay of about 100 ms. The resistor must also be capable of supporting several operations per minute. Protection of the soft-start resistor, if the contactor should fail to switch, is provided by a thermal device.



**Fig. 9:** Inrush current for 2.5 kW switch-mode (left) and 90 kW thyristor-controlled (right) converters

### 4.3 Power transformer protection

High-power converters must be designed to accommodate interlocks from external transformers and isolating switchgear. These signals include Buchholz (transformer gas), over-temperature and low water flow. They will generate a fault and/or alarm indication, which can be used as warning signals—alerting users of a potential failure—or to trip the converter.

When specifying a transformer for converter use it should be rated for rectifier operation, as the input current will have a high harmonic content and will generate high losses due to skin effect in the winding. The type of insulating material specified will determine the maximum hot-spot temperatures that are allowed for safe operation. To ensure a long lifetime for the transformer, the allowed temperature rise is normally fixed for an insulation class lower.

Transformers can be designed and tested to sustain a phase-to-phase and phase-to-earth short circuit, removing the need for semiconductor fuses and improving reliability. The transformer must be capable of sustaining the fault current, without damage, until the circuit breaker opens. This is particularly relevant when a large number of power converters is installed, as fuses are susceptible to ageing.

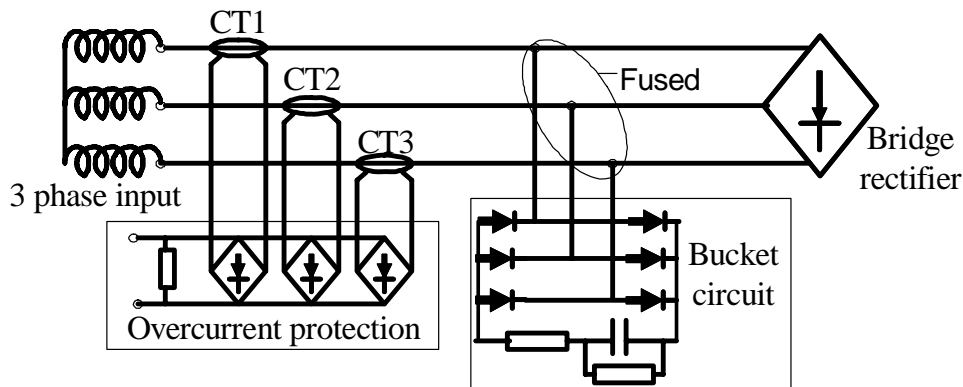


Fig. 10: Surge and over-current protection

Surge protection is commonly provided by capacitor-resistor networks. If connected across each of the incoming lines, they will protect the rectifier from high-voltage transients. It is also possible to use surge suppressors, voltage-dependent resistors or spark gaps. The most popular method is to connect a low-current bridge rectifier across the incoming line, with a reservoir capacitor across the dc output. This is known as the ‘bucket’ circuit and includes a discharge and damping resistor. The rating of this circuit depends on the transformer rating and the stored energy at switch-off. Fuses are used to protect the rectifier bridge against short circuit.

ac current transformers (CTs) measure the line current feeding high-power converters. If over-current is detected, due to a bridge imbalance on a 12-pulse rectifier, thyristor failure or regulation calibration error, then the switching circuits are inhibited and the main contactor opened. The CT associated electronics are generally integrated with the converter control system and can be set accurately.

### 4.4 Thyristor suppression

It is standard practice to connect a capacitor-resistor network across each thyristor, because the hole-storage generates voltage transients at the end of commutation. The component values depend on transformer reactance, the inverse peak current (which depends on the  $dI/dt$  and the forward current before commutation) and the stored charge in the semiconductor (value given in manufacturer’s data sheets).

#### 4.5 Fuse links

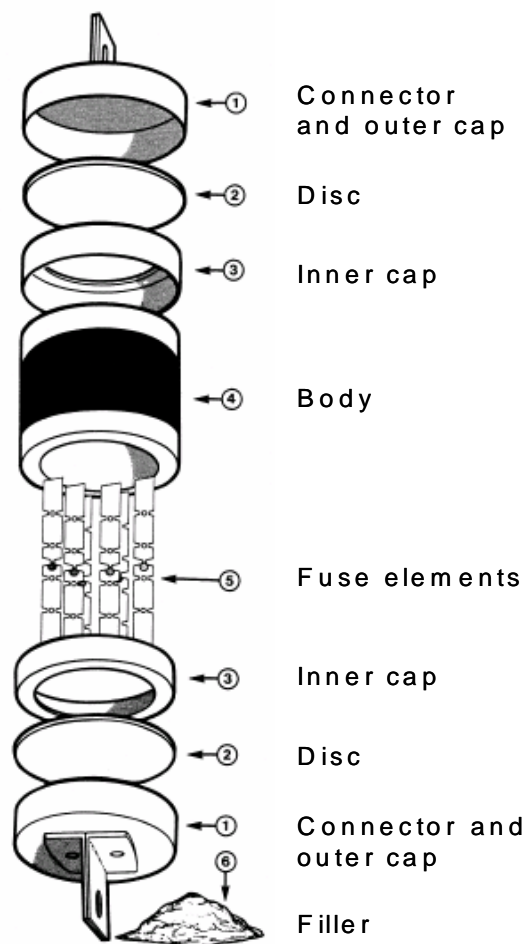
The speed at which a fuse operates is directly linked to the level of the fault current. For example, a 100 A fuse link might take several minutes to operate at 200 A but would operate in a fraction of a second at 1000 A. A graph plotting the operating time of a fuse link against fault current is called a time–current graph. Such graphs are produced according to BS or IEC standards and are termed average curves.

When a fuse link interrupts a high value of fault current, it cuts off the current before it can reach its full value. Current limiting is the most important feature of fuse link operation.

The  $I^2t$  or joule-integrated data is a calculation of energy, which is controlled or cut off through the fuse link. Two values or curves are always given for each fuse link:

- (1) minimum pre-melting  $I^2t$ ,
- (2) maximum clearing  $I^2t$ .

The first represents the amount of energy let through by the fuse link from the start of the fault until the time the fuse link actually begins to operate. The second represents the total package of energy let through by the fuse link until the instant when the fuse link finally interrupts the fault current.



**Fig. 11:** Fuse link design

#### 4.5.1 Semiconductor fuse links

Like many other circuit components, the semiconductor is sensitive to excesses in both current and voltage. When an over-current is evident the wafer-thin sections of the device overheat and are damaged. Similarly, when the current is not flowing through the device, but a high circuit voltage is present, the device will again be damaged.

Protection of expensive semiconductors can only be achieved by devices having an extremely rapid circuit-breaking action coupled with current and energy limitation. Fuse links do not depend upon a mechanical system, with inherent inertia, in their mode of operation and are therefore able to respond immediately to the thermal state of semiconductors.

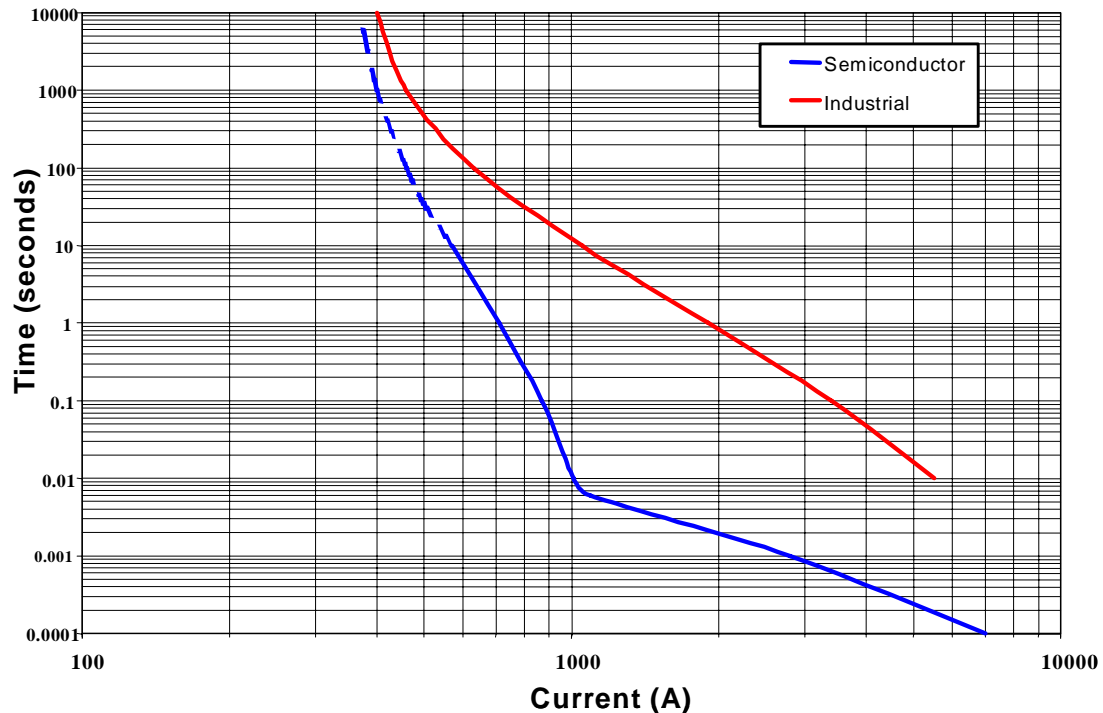


Fig. 12: Time–current graph for a 250 A fuse

Fuse links designed to protect semiconductors incorporate elements machined to finer tolerances and rarely employ the M-effect: a special alloy melted onto elements to ensure cooler running, as used in the industrial range. A fuse link element with finer tolerances will reduce the ability of the fuse to provide low over-current protection, and will therefore provide increased protection to the semiconductor. As a consequence of interrupting the current flow more quickly, an over-voltage is produced by the fuse link. This voltage must be limited or other circuit components (including the semiconductor) could be damaged. To limit this over-voltage, additional bonding agents are added to improve the sand compaction around the element, reducing the energy of the arc on operation.

A fuse should be selected according to the following criteria:

- nominal current of semiconductor to be protected;
- $I^2t$  of fuse needs to be less than the  $I^2t$  of the semiconductor;
- fuse over-voltage rating (when a fuse clears the resultant  $dI/dt$  produces a voltage transient) should be greater than the system over-voltage rating.

Many fuse links for the protection of semiconductors used in Europe incorporate indicators. These are similar to those used in industrial fuse links and may be positioned at one end or in the central regions of the fuse link body. As well as giving local indication as to the status of the fuse links, these devices may be adapted to operate micro-switches so that remote indication of the fuse operation can be provided.

**Table 1:** Industrial low-voltage switchgear and fuse standards

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

## 5 Internal protection

### 5.1 Output monitors

#### 5.1.1 *dc current transducers (DCCT)*

Magnet power converters are usually current controlled in order to obtain a reproducible magnetic field. Since the introduction of high-precision dc current transducers the high-current shunt is rarely used for stabilization. The zero-flux type of DCCT is the preferred design; it detects any change of field in its core and reacts by injecting a balancing current, which can be measured to much better than a single part per million (ppm) resolution. As the DCCT is critical to the power-converter performance, its reliable operation must be ensured. Detecting a calibration change in the DCCT is often identified by degradation in experimental performance. Regular calibration can minimize this, but if a large number of converters are employed this can be impractical.

Some designers now install two DCCTs and separate the functions of stabilization and monitoring. By comparing these two outputs, the unit's calibration can be verified and the user warned of potential problems. This is not ideal as the price of a precision DCCT is a significant fraction of the power-converter cost, especially at low power levels.

Alternatively, a calibration winding can be added to the DCCT head; this will allow the power converter to perform regular self-calibration checks. It requires an accurate and highly stable current source as a reference signal for the auxiliary winding, but this method is also expensive. Its cost is expected to reduce as the technology is developed.

The modern DCCT usually provides an output valid signal, which means the converter is working within its allowed operating range; this can be used as a warning or to trip the unit. The zero-current interlock is often used with polarity change-over switches so that their operation can be inhibited until the output current is zero. When using highly inductive loads, the current discharge can be slow and the DCCT can be used to delay power-converter turn-off or inhibit re-energizing during the discharge.

### 5.1.2 Earth protection

It is unusual to allow the load and the converter to be left floating; normally a connection to ground is made somewhere. Earth faults can arise due to damaged insulation, water conductivity, or accident. An adequate low-impedance earthing system is required, which allows sufficient current to flow to activate the protection. Usually the connection to earth is provided at one of the converter output terminals, but with mid-point earthing the maximum voltage to earth at the magnet load will be half the maximum dc voltage.

For large accelerators with many magnets connected in series, it is necessary to separate the power converter into several subunits, with each unit left floating. Only one unit will be earthed at one point with a low-value resistor. The voltage on this resistor will be monitored and used as an earth-current monitor. If this current exceeds a certain value, it will be detected and the power converter switched off.

If the converter has to be completely floating then differential detection may be convenient. This type of detector is normally used on ac distribution systems.

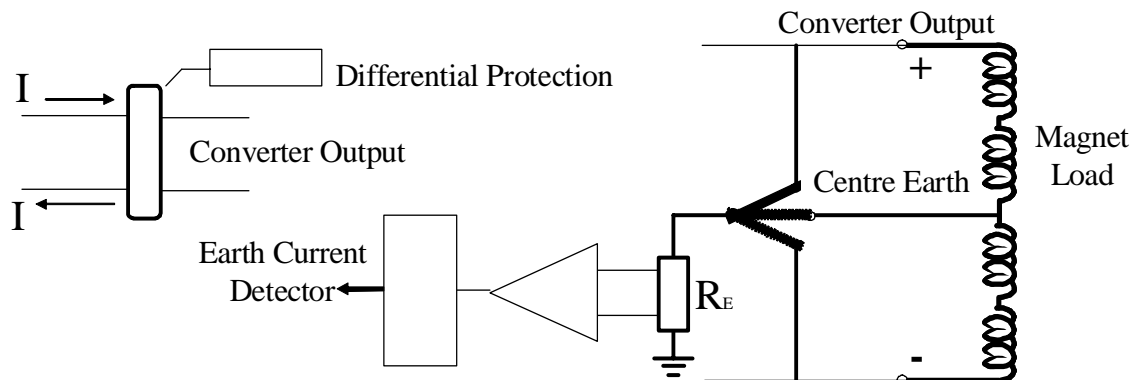


Fig. 13: Typical earth-leakage detection circuits

### 5.1.3 General protection

Internal protection should be provided to match the power-converter technology. Filters and chokes are commonplace but vary widely in size. Low-power units often rely on the input circuit breaker to protect the low-frequency line filter and thermo-contacts to prevent overheating of chokes. The larger power converters are designed with fuse protection or current transformers to stop excessive ac current.

If series regulation is employed then indication of a semiconductor failure should be provided. Converters that make use of several parallel devices or circuits for increased rating or redundancy must have a minimum number of operational semiconductors for reliable performance. Once this threshold is reached, the power converter must be tripped to prevent the breakdown cascading and the loss of all semiconductors.

The power-converter internal controls should be designed to survive short interruptions. This can be achieved with uninterruptible power supply (UPS) backup or by auxiliary supplies with three-phase input that allow the loss of one phase without affecting operation.

## **6 Load protection and interlocks**

### **6.1 Magnet interlocks**

In case of electrical insulation damage to the magnet coils or short circuit to earth on the magnet terminals, internal earthing protection of the power converter will operate, limiting the damage to the system.

Restricting the maximum output current of the converter may not be enough to protect a magnet from damage if the converter is not matched with the load, or if the cooling water for the magnet is stopped. Thermo-contacts, fixed to one magnet coil, and to all coils if parallel water feeds are used, protect the coils against overheating. In order to interrupt the current before the trip temperature of the thermo-contact is reached, the magnets are normally equipped with a flow meter at the water outlet of the cooling system. In addition, some magnets are equipped with a water-pressure monitor as an extra means of protection.

A clearly visible red emergency push button can be mounted on the magnet to enable rapid power-converter switch-off. This button is also used as secondary protection to ensure converters can not be turned on while personnel work on the magnets. Cables of adequate insulation and cross-section are used to interconnect the individual magnets. Usually the magnets have covers over their busbars (IP2X classification) and as long as these are not removed, no live electrical parts can be touched. Safe working procedures are usually adequate to allow personnel to work in the accelerator and beamlines even if the magnets are energized. Additional protection can be incorporated by fitting switches to the busbar covers, which activate an interlock if removed and turn off the converter.

The connection between the magnet interlock contacts and the power converter must be reliable as these are the only means of protection against overheating due to water-flow interruptions or over-current. When changing the magnet to a different power converter, care must be taken to ensure that their corresponding interlocks are also changed. If a load is powered by several converters, strict procedures are critical and any load protective interlock must switch off all converters.

The use of several interlocks of different types (thermal, water flow supervision) is enough to produce redundancy of magnet protection—a desired feature.

### **6.2 Superconducting magnets**

The time constants of superconducting magnets, including their cables are very long. In order to build up the current, only a limited voltage is allowed to prevent over-rating the converter. If the converter trips, or the mains voltage fails, the only voltage available for reducing the current to zero is the voltage drop in the last conducting semiconductor and the voltage drop on the cables and connectors. It may take several minutes or even hours before the energy within the magnet is dissipated. The semiconductors must be able to carry this current during all this time without any external cooling. If the converter needs water or forced air cooling then it has to be over-rated to withstand the energy transferred from the magnet or fitted with a separate discharge element that can work without any active cooling (for example, free-wheeling diodes).

Another major problem with superconducting magnets is the loss of superconductivity, referred to as a ‘quench’. When a magnet quenches, current has to be extracted from the magnet to minimize magnet stress. A quench detector looks for a dissymmetry in the voltage across the coils and activates



a fast trip to remove the magnet's supply. The energy stored in the magnet is then dissipated in a separate discharge circuit.

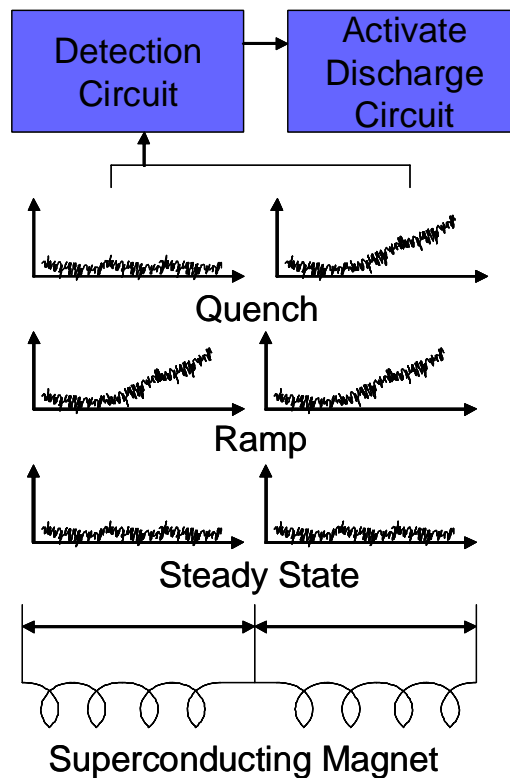


Fig. 14: Quench detection circuit

During normal operation, the energy from the magnet can be returned to the feeding mains by replacing the diode of the discharge circuit with a thyristor.

### 6.3 Crowbar circuits

Some power converters are designed with an active crowbar circuit. These devices are normally used when there are very high load-inductances. They protect the converter from excessive voltages if, for example, the feeding ac supply or internal controls fail.

Crowbar protection systems, with virtually absolute reliability, are required in line-commutated converters to protect high-value equipment such as klystrons and inductive output tubes (IOT) from damage. They consist of a high-power, high-speed switch (or number of switches) capable of diverting energy stored in the circuit capacitors and inductors safely away from the load, dissipating it elsewhere in the circuit.

This stored energy can destroy valves if a spark should occur between cathode and body or cathode and modulating anode. In addition, failure of the water cooling to the valve or failure of the focus supply will rapidly result in failure of the valve. The old crowbar systems were designed with ignitrons or thyratrons, but solid-state versions are now available. Alternatively switch-mode converters can be employed, which have inherently low stored energy such that they cannot damage the valve.

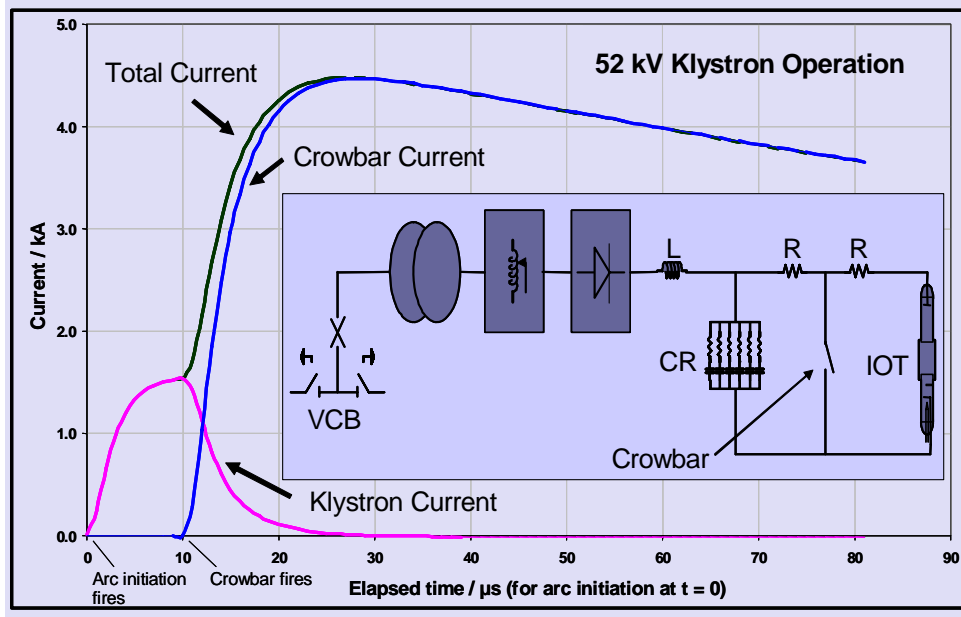


Fig. 15: Typical klystron crowbar and simulated operation

## 7 General diagnostics

### 7.1 Causes and symptoms

When a power-converter fault occurs, it is the primary objective of the service engineer to find the cause (a person or event that makes something happen) by analysing the symptoms (a sign, indication that something has occurred) and repair it as quickly as possible. The initial fault can manifest itself in a variety of ways: the operator experiencing reduced performance, control limitation, or often physical signs such as visual (damage), smell (burning), and audio (lack of or excessive fan noise or misfiring).

Clear diagnostics are vital both locally and, more importantly, remotely as the service engineer can plan a strategy for repair while communicating from the main control room or via an Ethernet connection. All service engineers must be approved personnel who have received the necessary training and been instructed in the relevant safety procedures. The test equipment used by the service engineer when analysing a fault must be fit for the purpose and include an appropriate calibration test certificate.

Power-converter faults can vary widely, from a simple thermal trip caused by a loss of coolant or broken thermal contact to stability issues due to out-of-tolerance components or intermittent breakdown. Most failures on power converters can be identified quickly and repaired; but when a power converter is causing, for example, a beam performance issue, detailed investigation may be required.

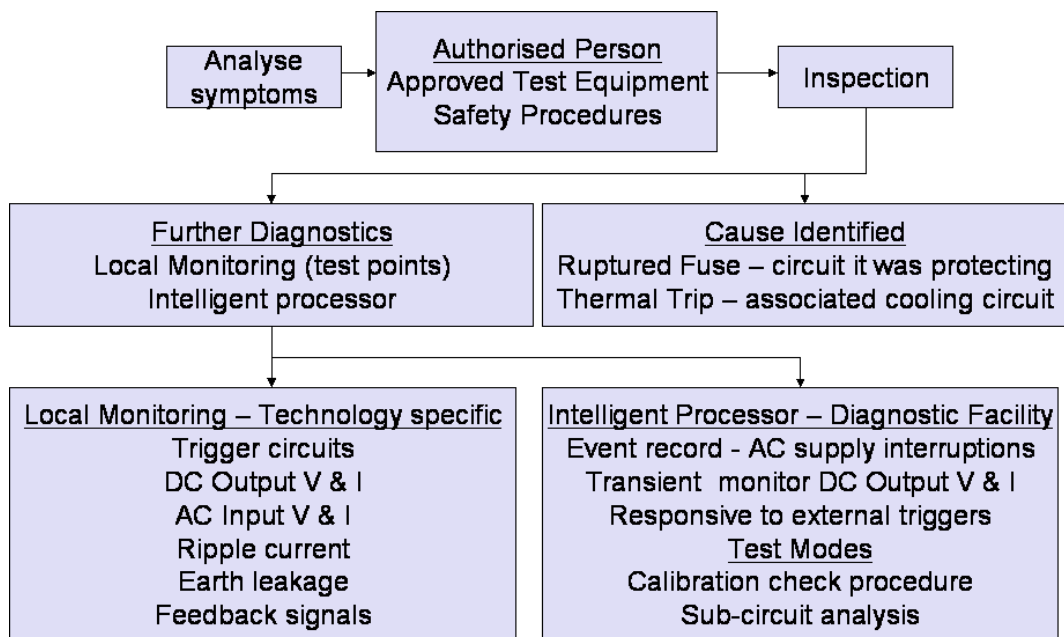
All modern accelerator power converters are specified as high performance, but there are many factors that contribute to achieving high performance, including reliability and repairability, with reliability arguably the most critical. Basic good design strategies can be incorporated to improve reliability, such as utilizing passive protection (suppression circuits) and ensuring that components have been chosen with generous safety factors. A power-converter design should be chosen with minimal component count and a topology or operating system that accommodates the simplest solution.

The reduction in electro-mechanical components used in power converters has improved reliability, but circuit breakers are still normally required and difficult to avoid. If circuit breakers are required, it is advisable to limit the number of operating cycles and make them easy to replace.

Protection circuits must be fail-safe, reliable and only trip when required. Interlocks should only be included if really necessary and protection-circuit design kept as simple as possible.

## 7.2 Diagnostics

Power-converter failures will inevitably occur at some time and repairability is then important. Accelerator downtime can be reduced by making the systems modular so that a simple replacement can be made by a non-specialized member of staff. Designers should also consider providing a ‘universal’ spare converter to reduce repair time and the quantity of spares held.



**Fig. 16:** Fault analysis procedure

Diagnostic facilities will assist the engineer in analysing the initial breakdown and repairing the faulty unit once removed. The amount of diagnostics employed within a power converter will depend on the application, chosen technology and rating. It is important that the designer balances the level of diagnostics against unit replacement and cost requirements.

If effective diagnostics are installed, they will

- minimize accelerator downtime or repair time;
- simplify the training for engineers;
- reduce live working during fault analysis.

When a service engineer is analysing, for example, an intermittent breakdown, it can be difficult to identify its cause. On facilities with large numbers of power converters, it can often be time consuming to find the unit actually failing. Most modern power converters utilize intelligent processors, mainly for controls interfacing, but designers have rapidly developed their functionality for diagnostic and control dynamics. They can be programmed to record occurrences within the converter when triggered by a beam instability or internal regulation change. A correlation of these

occurrences can then be made and the power converter causing the instability found. The offending unit can then be replaced or repaired in position.

If limited or no intelligent diagnostics facilities are available, local monitoring may be required and the designer and service engineer must ensure that all relevant test points are accessible and safe. This will prevent the service engineer from analysing the power circuits with potentially live terminals exposed. When internal access is necessary for fault finding, any exposed terminals need to be protected to IP2X Standard or a Live Working Permit has to be issued with appropriate personnel protective equipment (PPE).

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