

Information Sheet

Using Thyristors In Heating Control Applications



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What are Thyristors?

The terms 'thyristor' and S C R (silicon controlled rectifier) are synonymous. The thyristor is a silicon semiconductor device, first made in 1957 in the laboratories of the General Electric Co.. As the name S C R implies, the device conducts current in only one direction, and two are required in inverse parallel connection to control an AC heating load. Unlike a diode, the thyristor is normally non-conducting in both directions, but when forward biased can be switched from a non-conducting to a conducting state by injecting current into a gate electrode. Once conducting, the phase control thyristor with which we are concerned can only be turned off by reducing the current flowing through it to zero. When controlling an AC application this happens automatically on each zero crossing of the waveform.

In industrial applications the terms 'thyristor' and 'S C R' are often applied loosely to assemblies of devices, mounted on heatsinks, and complete with control electronics, more correctly called thyristor stacks. The term 'solid state relay' is often applied to a potted assembly of thyristors and control electronics, with or without heatsink. Solid state relays are only applicable to lower power applications (up to about 75A), and care must be exercised when using them to ensure that the current ratings apply at the ambient temperature in the control panel. In general the devices in a solid state relay are smaller than in a thyristor stack of similar rating plate current rating, and may well have a lower blocking voltage and simpler control electronics, making them less robust (but also cheaper)!

Control Techniques - a Brief Overview

There are two fundamental ways in which thyristors may be switched to control heating loads; whole cycle control and phase angle control.

With full cycle control the load current is switched on for complete cycles of the supply, and the average power in the load is controlled by altering the ratio of on cycles to off cycles. This control technique is used in the following generic forms; fast cycle and slow cycle burst fire, single cycle burst fire.

With phase angle control the individual cycles of the supply are chopped, and the average power in the load is controlled by varying the angle into each half cycle at which the thyristor is switched on.

The major differences between the two control techniques are:-

- 1 Full cycle control offers no control over the load voltage or current when the thyristors are on. The load always sees the full supply voltage, and will draw the current defined by Ohm's law - Supply voltage / load resistance. This control technique cannot therefore be used in any application which requires current or voltage limitation. Current limit is required with heating elements which have a low resistance when cold. The current must be limited until the elements warm up and attain their normal working temperature. Full cycle control minimises radio frequency interference and harmonic generation, and for these reasons is normally preferred over phase angle control in most applications.
- 2 Phase angle control offers voltage and current limitation or control, but this is associated with high levels of radio frequency interference and harmonic generation, and a poor power factor.

In heating applications the main feedback control loop normally includes a temperature sensor and PID temperature controller. The thyristor stack responds to a demand signal from the temperature controller and adjusts the average load power accordingly. The stack may be fitted with local feedback circuits which monitor the line or load voltage and load current. In most applications this is not necessary, but can help in reducing temperature variations by immediately compensating for changes in these parameters, rather than relying on the temperature sensor to sense the effect. Another special requirement in phase angle applications may be the minimising of any DC component in the load current.

Summary of Common Heating Loads and Suitable Control Techniques

The following are commonly encountered heating loads:-

- 1 Straight resistive heating loads, in which the resistance of the elements does not have a significant temperature coefficient. This covers the majority of applications in ovens and furnaces operating up to 1000°C.

Applicable control techniques are

Burst firing

Single cycle burst firing (where a fast response is required)

Phase angle (not normally recommended)

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- 2 Transformer coupled heating loads. In which a transformer is interposed between the thyristor controller and the load; eg where the resistance of the elements is very low. A typical application is graphite elements in high temperature furnaces. When thyristors are used to feed transformers the integrity of the firing circuits is very important. They must be very stable and immune to interference, as otherwise the transformer may be subjected to inrush currents or a DC component, resulting in core saturation, overheating, blown fuses, and generally unreliable performance.
- Applicable control techniques are Cycle synchronised burst fire with delayed start
 Phase angle start burst fire
 Phase angle (where a fast response is required)
- 3 Heating loads in which the element resistance has a significant temperature coefficient, including loads which are transformer coupled and the element resistance has a significant temperature coefficient. These tend to be high temperature applications with special resistance materials, eg platinum wire, or molybdenum disilicide.
- Applicable control techniques are Phase angle
- 4 Silicon carbide elements. Historically phase angle control was the preferred technique for use with this material. However, in Europe single cycle burst fire has now become the preferred technique. It is important not to temperature cycle silicon carbide elements (as would happen by cycling them on and off at moderate rates eg a few cycles per minute) as this can result in premature failure. The resistance of silicon carbide elements is lowest at an intermediate temperature below the normal operating temperature, and the current rating of the thyristors must be capable of feeding this lower resistance. As silicon carbide elements age their resistance increases, and at the end of their life they may have twice the resistance they had when new. This must be considered when designing a furnace.
- 5 Infrared quartz elements. These elements have a very fast response, and historically phase angle control was used. Again, single cycle burst fire is now becoming a preferred technique.

Factors to consider when applying Thyristors

A number of factors need to be considered when applying thyristors. These are listed below, and considered in more detail in the subsequent sections:-

- 1 Voltage 'flicker'.
- 2 Harmonic distortion, including sub-harmonics.
- 3 Power factor.
- 4 Conducted and radiated electromagnetic interference.
- 5 Temperature rise in the control panel.
- 6 Over-current and short circuit protection.
- 7 Neutral currents.
- 8 Safety.

Control Techniques and associated Design Considerations

- 1 **Burst fire (including delayed start)** 

In burst fire mode the thyristors are used in the form of a 'solid state contactor'. The thyristors are cycled on for a period, and then off. By varying the length of the on period relative to the off period the power to the load may be controlled. Thyristors have two advantages over contactors; they have a much longer operating life and are silent in operation, and by using 'zero voltage switching' electromagnetic interference can be made much lower (there is no contact arcing). This mode of operation results in a power factor equal to that of the load, and creates minimal harmonic distortion, because the current is either fully on or fully off. The on/off cycle rate may be set faster than with contactors, as there is effectively no wear out mechanism. This may be useful when controlling loads with a short thermal time constant; however, the cycle time should not be set shorter than necessary, as remaining electromagnetic effects associated with the switching are thereby increased. A further effect which is aggravated by cycling speed is that of voltage 'flicker'. This is the effect whereby the supply voltage drops when the load is switched on, causing undesirable effects on other equipment, particularly lighting, but also fans etc. This effect must be considered particularly when the heating load becomes a significant proportion of the installed capacity. In heavy industrial environments it is not normally a problem, but in light industrial and commercial installations it may cause a problem. It can also present a problem in generator-supplied installations, affecting the generator speed control.

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Burst fire with zero voltage switch on cannot be applied to transformer loads, because of the large transformer inrush current which results. Special precautions have to be taken to apply burst fire techniques to transformer loads. In particular, the switch on must occur near the peak of the voltage waveform. This results in higher electromagnetic emissions, but these are still lower than with any other technique which can be applied to transformer control.

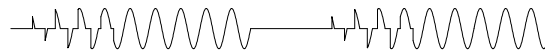
In 3-phase 3-wire applications it is common practice only to control 2 of the 3 lines. This reduces the size and cost of the installation, and also reduces the heat dissipation. A potential disadvantage is that in the 'off' condition all the heater elements are at line potential over their whole length. This may increase earth leakage to an unacceptable level. The elements are obviously not safe to touch in this condition, but thyristors should not in any case be used to provide a safe off condition under any circumstances, and independent isolation facilities must be provided.

2 Single cycle burst fire



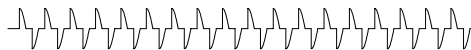
This technique applies burst fire with the fastest possible cycle time. It is thus primarily aimed at loads with a short thermal time constant. At 50% power the current is applied 1-cycle on, 1-cycle off. At 99% power current is applied 99 cycles on, 1 cycle off. At 1% power current is applied 1 cycle on, 99 cycles off etc. The technique cannot be used with 3-phase 3-wire loads except where only 2 lines are controlled, and results in a significant neutral current on 3-phase 4-wire loads. The technique creates sub-harmonics, which may present a problem in large installations. In 3-phase systems harmonic currents are also created, though these are significantly less than with phase angle operation.

3 Phase angle start burst fire



This technique is often used in the control of transformer loads. At the start of each on-period the thyristors are ramped to full conduction in phase angle (cycle chopping) mode, typically over 10 to 20 cycles. This eliminates transformer inrush. Significant harmonic distortion and electromagnetic interference is created during the phase angle ramp. The cycle time should be as long as possible to minimise these effects, and to maximise the power factor. The technique was developed to minimise the undesirable effects of phase angle operation (see below). The technique is applicable to single phase and 3-phase operation. In 3-phase operation all 3 lines should be controlled.

4 Phase angle.



This is the mode of control traditionally associated with thyristors (and triacs). The load current is controlled by only switching the thyristor on at a delayed point in each half cycle. The thyristor automatically switches off as the cycle passes through zero. This technique is sometimes known as cycle chopping, and everyday applications are light dimmers, portable tool speed controls, motor soft starts. In heating applications it should be avoided unless absolutely necessary. This is because it is associated with poor power factor (at low loading the power factor is extremely poor, and only 0.7 at 50% load), harmonic distortion, electromagnetic interference, and potentially high neutral currents in 3-phase 4-wire systems. All of these effects are likely to be very significant, because of the high currents associated with heating loads. (It does not however cause voltage flicker!).

The technique has to be used where control over the load voltage or current is required, particularly for current limit control. This may be necessary if controlling a heater with very low cold resistance. It will be necessary to limit the current until the heater has warmed up.

Other Design Considerations

Temperature rise in the control panel

Thyristors and solid state relays dissipate heat when conducting. The power dissipated is approximately 1.5 to $2 \times$ (RMS current) \times (Number of Controlled Lines). This power loss can cause a significant temperature rise in the control panel, and it is important to ensure that the maximum ambient temperature rating of the thyristors, cabling and other equipment in the panel is not exceeded. The majority of our range of thyristor stacks is rated for full current with a maximum ambient temperature of 50°C . Solid state relays pre-assembled to heatsinks are often only rated for full current at 25°C ambient. Solid state relays supplied loose must be fitted on a suitable heatsink to achieve their rated current.

Over-current and Short Circuit Protection.

To provide full protection for thyristor devices is not straightforward. In particular the use of HBC fuses (type gG or gL in Europe) alone will most probably not offer adequate protection against either overload or short circuit. Special semiconductor fuses (type aR) provide correct protection against short circuits ($1/2$ cycle I^2t), and are normally mounted on the thyristor stack. However, the characteristics of these fuses for low and moderate overloads are not defined. Also to reduce their operating temperature and susceptibility to fatigue failure in burst fire applications the current rating of the semiconductor fuse is often higher than the load current rating, and proper overload protection is not provided. Separate fusing must therefore be provided to protect against overloads. To provide overload protection for the cabling and short circuit protection it is necessary to fuse the cables with gG or gL type fuses, with semiconductor fuses (normally fitted on the stack) to provide the short circuit protection.

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Harmonic and EMC Filters

In all applications filters will need to be considered to comply with statutory requirements. Filters fall into two categories: radio frequency and harmonic. The purpose of radio frequency filters is to ensure compliance with the EMC directive (in Europe) with regard to conducted radio frequency emissions on the supply lines. These will be required in any application with phase angle operation, and may well be required in burst fire applications which do not have zero-voltage switch on. Even applications with zero-voltage switch on may cause problems due to noise associated with the zero crossing commutation, particularly in non-industrial installations, but simple capacitive filters will probably be adequate.

Harmonic filters are much bulkier. They should only be necessary in installations with pure phase angle operation.

Thyristor stacks manufactured by Caledon Controls have been designed with low levels of emissions, and also have a high level of immunity to interference. Immunity is very important, as mis-firing caused by electromagnetic interference can be a serious cause of malfunctions in an industrial environment. For example, interference from motor drives causing thyristors to turn on spuriously, resulting in uncontrolled heating.

Neutral Currents

Significant neutral currents can flow in 4-wire 3-phase thyristor controlled circuits, even when the load is nominally balanced. For example, if a burst fire thyristor or solid state relay is fitted in each line but the firing is not synchronised, then the return current flows through the neutral. If the firing is synchronised a neutral current will still flow, because the firing of the thyristors occurs at zero voltage, and the switch off occurs at zero current. These firing points are 120° apart on each phase. This becomes important where a high switching rate is employed, or in single cycle operation. In these applications the neutral cable should be sized the same as the line cables.

In phase angle operation the situation is more complex. In a balanced system the neutral current is at a maximum and will equal the rated line current at 90° firing angle, when the actual line current is only 0.7 x rated line current. Unbalance of the load will increase the neutral current. In an application with current limit the rated line current may be taken at a reduced firing angle, and the neutral current can be as much as 1.7 x rated line current at low firing angles. It may therefore be necessary to have a neutral cable rated for between 1.5 and 2 x the line current. The supply transformer must also be considered in large installations. This situation can be avoided by using a 3-wire system.

Safety

Thyristors must never be assumed to be completely non-conducting. Even in the 'off' state there will be a leakage current, which could be sufficiently high to be lethal to personnel. Separate provision for isolation must be provided.

In heating applications consideration must be given to the condition where a thyristor device fails short circuit, and control of the load current is lost. If this could lead to a dangerously high temperature, then independent provision must be made to switch off the current. This may take the form of an independent sensor controlling a contactor in series with the thyristor stack, or tripping an under voltage release on the circuit breaker supplying the thyristor stack. Alternatively the load voltage may be monitored and compared with the thyristor control signal, generating an alarm output to trip the circuit breaker if load voltage is present in the absence of a control signal.