Electronic Power Units

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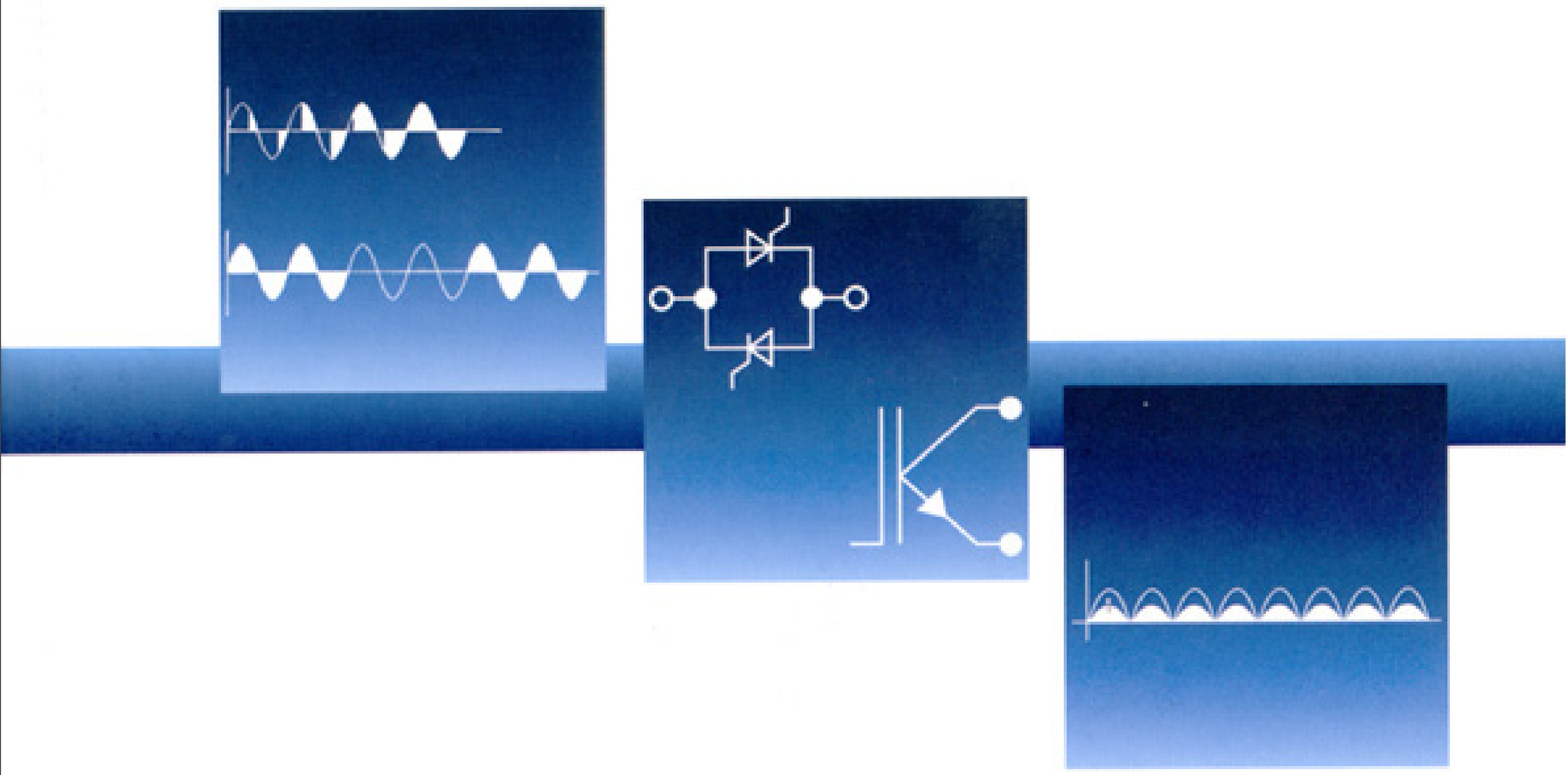

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Introduction

For simple applications, switching devices such as contactors or solid-state relays can be used to control electrical power. The electrical power in a process can be regulated by varying the ON and OFF times of these devices. But in many processes this provision of energy in large blocks will cause significant variations in the process output. As an example, it would not be possible to control lighting levels simply by using such two-state on/off switching elements. Neither could good temperature controllers be implemented in this way, since wide variations of the process variable are unacceptable in such an application.

Control elements such as variable transformers have been used ever since the beginnings of automation, as they permit a continuous variation of the electrical power. A variable transformer is, however, very expensive, subject to wear, and only permits slow adjustment.

This publication is intended to clarify the operating principles of electronically controlled power units, which are free from wear and have a very high rate of adjustment of the output level. The descriptions of the power units are generalized, but in some places they refer specifically to thyristor and IGBT power units from JUMO.

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1.1 The thyristor as an electronic switch

1.1.1 Structure and function

In a thyristor power unit the actual control element is the thyristor, a controllable silicon rectifier. It is formed by four successive semiconductor layers with alternate p- and n-doping between an anode and a cathode. The control electrode – usually known as the gate – is the p-region which is closer to the cathode.

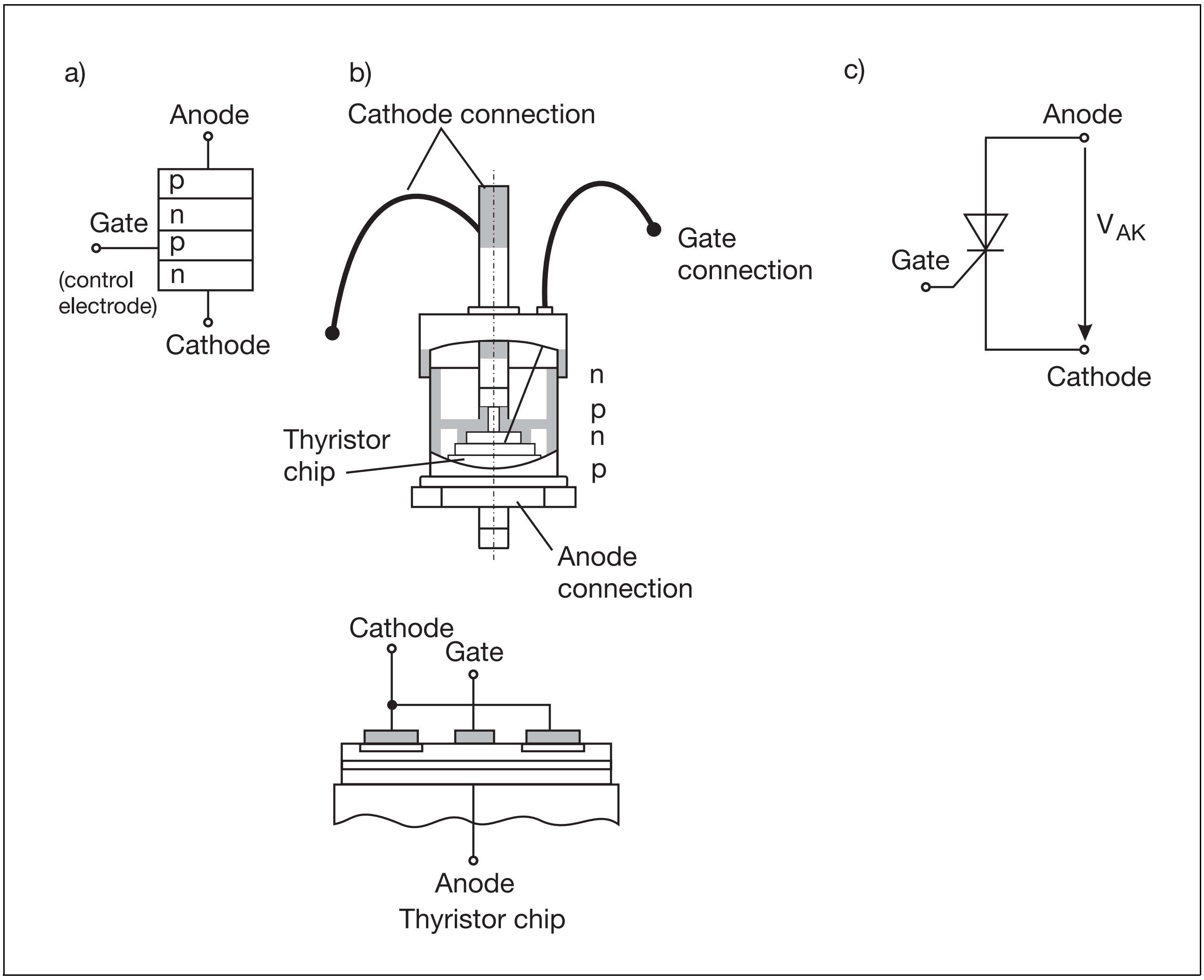


Fig. 1: a) schematic structure of a thyristor b) section through a thyristor casing, c) circuit symbol for a thyristor, with the voltage V_{AK} in the direction of conduction

If a positive (with respect to the cathode) control pulse of sufficient duration and amplitude is applied to the control electrode (gate) of a thyristor that also has a positive anode-cathode voltage, then the thyristor will snap from the high-resistance state into the low-resistance state. The thyristor is said to be *triggered* or *fired*. Once fired, the thyristor can no longer be turned off via the gate electrode. It will only snap back into the high-resistance state when the anode-cathode current falls below a minimum value, known as the holding current. In AC circuits this happens at the end of every half-cycle of the supply voltage, when the current drops to zero. If a resistive load is being controlled, then the current and voltage are in phase. With a resistive-inductive load, the zero point of the current waveform will have a phase shift with respect to the zero-crossing point of the supply waveform. These characteristics allow the thyristor to be used as a contactless electronic switch.

In the low-resistance (*on* or conducting) state, there is a voltage drop between the anode and cathode – the *on* voltage – of about 1 to 2V. This results in a power loss that is proportional to the current flowing, and heats up the thyristor.

In the high-resistance *off* or *blocking* state, a small current – the *leakage* current – still flows through the thyristor. This could be something like 20mA for a thyristor with a 100A rating.

A excessively fast rate of rise of the forward voltage V_{AK} (high $\frac{dv}{dt}$ value) can also fire the thyristor, even without a trigger pulse being applied to the gate. This uncontrolled firing is caused by capacitive currents flowing in the thyristor chip.

When the thyristor has been fired, the rate of rise of the load current ($\frac{di}{dt}$ value) must also not go above a certain critical limit, otherwise the thyristor may be destroyed through local overheating of the chip.

1.1.2 Protective measures

Various precautions must be taken to prevent thyristors failing in operation, and they are described briefly below.

The electrical power losses that appear as heat must be removed from the thyristor chip by adequately dimensioned heat sinks. The power dissipation can be calculated as the product of on-state voltage and the load current.

Excessive rate of rise (also known as *slew rate*) of the forward voltage can be prevented by using RC snubbers and varistors (voltage-dependent resistors).

The slew rate of the load current can be limited by an inductance in series with the thyristor. This is an especially important protection method for operation at high frequencies.

An ultra-fast semiconductor fuse should be used to protect the thyristor in the event of a load short-circuit. Effective thyristor protection can only be achieved if the fuse type used is the one specified by the manufacturer.

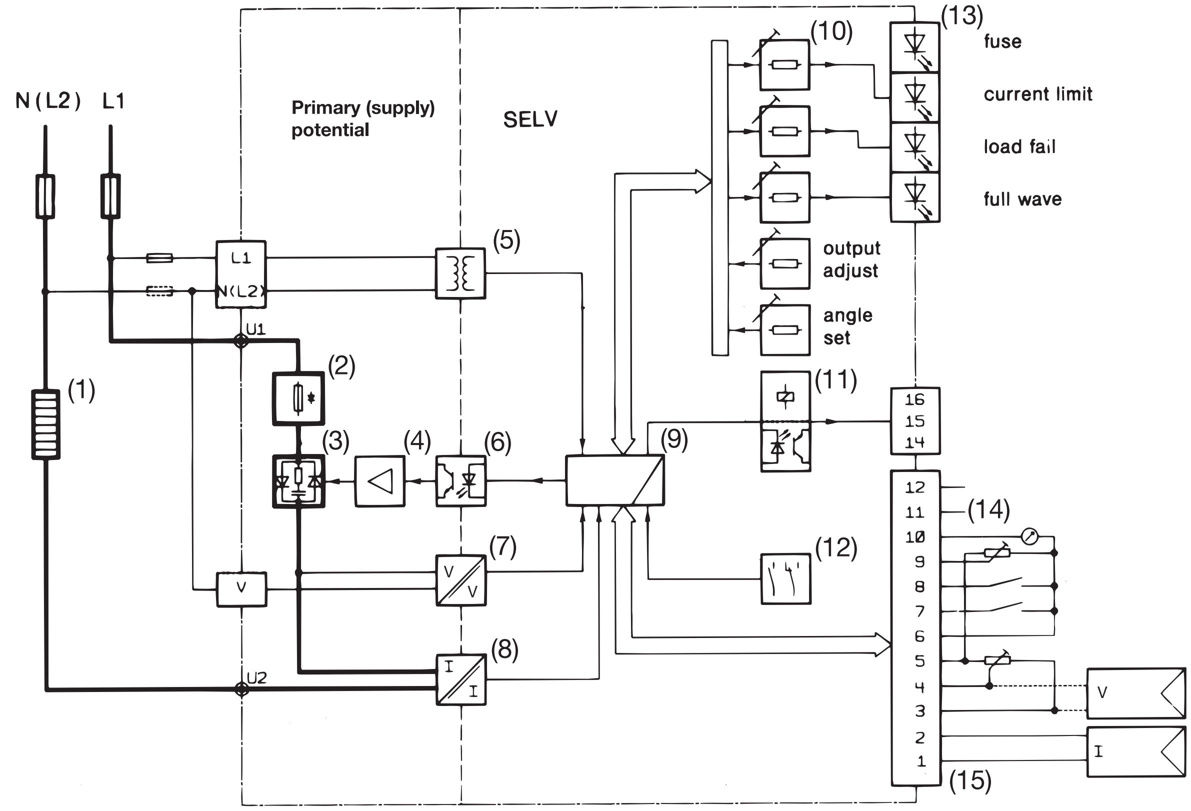
1.2 The thyristor power unit as a control device

Since a single thyristor can only be used to switch the current flowing in the anode-cathode (forwards) direction, two thyristors connected in anti-parallel are required to switch AC currents. Such thyristor modules can then be used for contactless regulation of the average current in AC or 3-phase circuits. This is achieved by equipping the thyristors with control circuitry to generate the required trigger pulses.

Now let’s take a look at the block diagram (Fig. 2), which illustrates the most important functions in a thyristor power unit:

The phase (L1) from the electrical supply feed is wired to the thyristor module via the ultra-fast semiconductor fuses (2). The thyristor module consists of 2 thyristors connected in anti-parallel, and can thus be fired on both positive and negative half-waves of the electrical supply. The RC snubbers prevent an excessive slew rate of the anode-cathode voltage and a resulting unintended triggering of the thyristors. The semiconductor fuses (2) break within one half-wave of the supply voltage, thus avoiding destruction of the thyristors in the event of a load short-circuit. The voltage and current are measured (7, 8) between the thyristors and the load, which is connected to the neutral conductor.

The triggering/firing of the thyristors (3) is carried out by the control electronics (9) via an optocoupler (6) and a driver stage (4). The output level is set externally by standard signals or a potentiometer connection (15).



(1) Load
(2) Ultra-fast semiconductor fuse
(3) Thyristor module with RC snubber
(4) Driver stage for thyristor module
(5) Power supply for control electronics
(6) Optocoupler
(7) Voltage transformer
(8) Current transformer
(9) Control electronics
(10) Front panel trimmer
(11) Fault signal output
via relay or optocoupler
(12) Configuration switch
(13) Signal LED
(14) Master-slave connection
(15) Output level setting,
control inputs,
actual (power level) output

Fig. 2: Block diagram of the JUMO thyristor power unit TYA-110/3

1.3 Operating modes

There are two basically different methods of controlling two thyristors connected in anti-parallel to achieve continuous power control for an AC load. The first method is phase-angle control, the one commonly used in inverter technology. The second method switches the load current on and off in a certain pattern and always at the zero-crossing points of the supply voltage, and this is known as burst-firing control.

When using burst-firing control, a thyristor is always switched on for a whole number of cycles of the supply voltage. If, for instance, the output level of the controller is set to 1% , this means that the supply is switched through to the load for one complete cycle, and then disconnected for 99 cycles.

However, in many processes (such as a lighting control system) these pulses of energy cannot be smoothed out and the result is a fluctuating output level (for example, lights would flicker).

Since phase-angle control switches on and off within each half-cycle of the supply voltage, this method is the one that produces the smallest fluctuations of the output level. Phase-angle control is therefore used whenever burst-firing cannot provide sufficiently fine dosing of the power fed into the control loop.

1.3.1 Phase-angle control

When using phase-angle control, current flows through the load under control during every half-cycle of the supply voltage. The current flows from the instant of firing until it naturally stops at the zero-crossing point (Fig. 3).

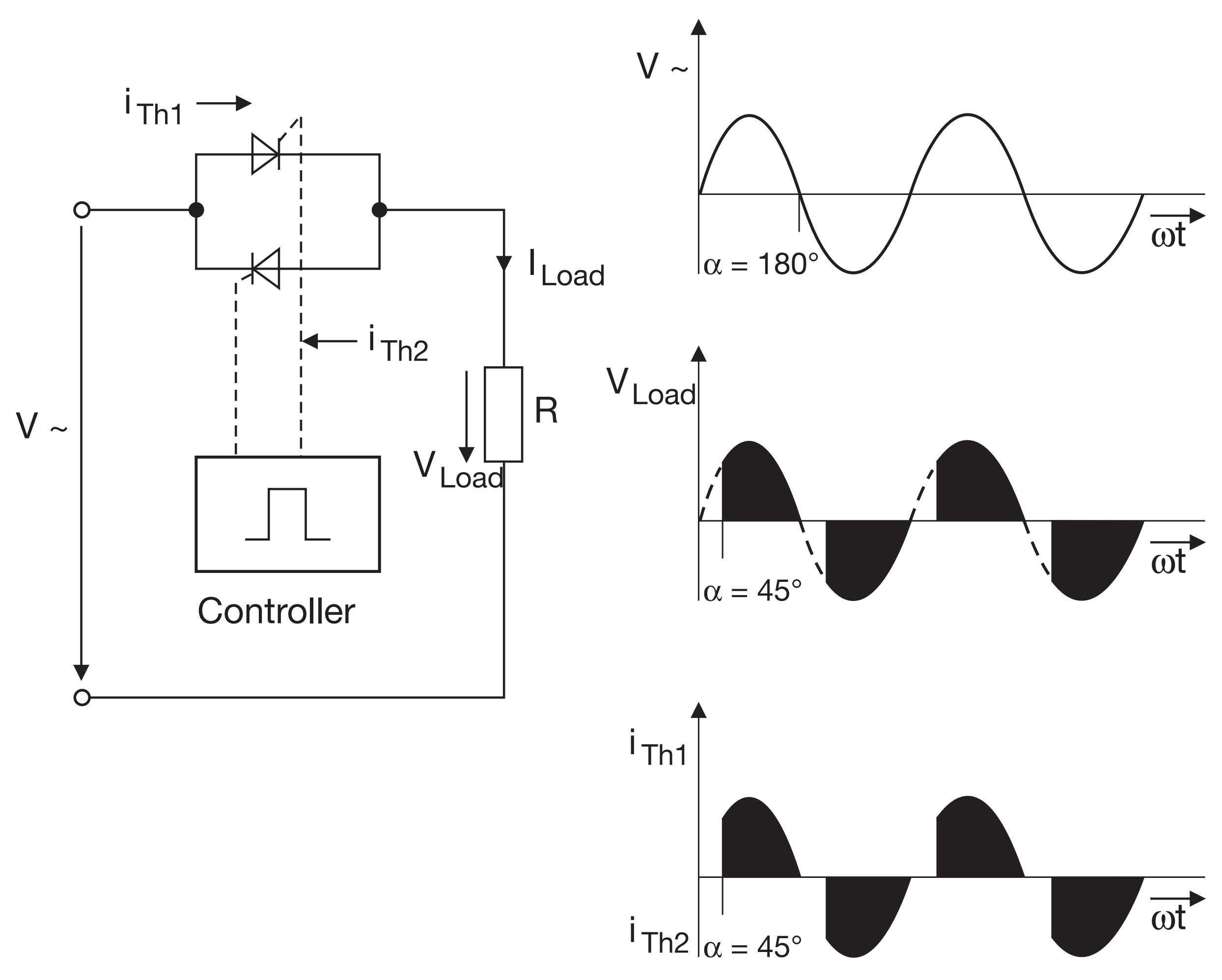


Fig. 3: Current and voltage waveforms for phase-angle control of a resistive load

$V\sim$ = supply voltage

V_{load} = load voltage

I_{load} = load current

i_{Th1} = load current through thyristor 1

i_{Th2} = load current through thyristor 2

α = phase angle

ωt = electrical phase angle at time t

The angle between the zero crossing of the supply voltage and the trigger point for firing the thyristor is known as the phase control angle or firing angle α. By changing the firing angle the average value of the AC voltage on the load resistor R can be continuously varied from its maximum value, when $\alpha = 0°$, to 0V when $\alpha = 180°$ (α is always an *electrical* phase angle).

Fig. 3 shows the relationships for a firing angle α = 45°. When α = 0° the output is at a maximum, i.e. the supply voltage is applied to the load without interruptions. On the other end, when α = 180° the voltage is continually blocked by the thyristor through the half-cycle. The dotted line shows the voltage waveform while the thyristor is in the blocking (off) state at a firing angle of 45°.

This mode of operation is suitable for resistive, inductive and resistive-inductive loads. In the first case, the load voltage and current are in phase, but in the other cases, the current lags behind the voltage. Thyristor power units from JUMO have a built-in soft-start circuit for transformer loads and a current limiting function, to ensure that no excessively high current flows when the load is switched on for the first time. The phase angle starts at α = 180° (completely cut back) and is then gradually advanced to the required control angle.

The advantages of phase-angle control are the fine control of the power output and the fast response time, which makes it possible to use it for very fast control loops. Current limiting can also be implemented in this way.

The disadvantage of this mode of operation is the generation of harmonics by the fast transitions of the cut-back half-cycles of the supply at the firing point and the HF interference that this produces. Another disadvantage is that a reactive power component appears, even when driving a resistive load. With resistive loads this is entirely due to the phase-angle control, and it is therefore known as phase control reactive power.

The generation of the phase control reactive power can be understood if one studies the Fourier analysis of the cut-back half-cycles of current. These can be represented by sinewaves of various harmonic frequencies superimposed upon the fundamental frequency. The phase shift of the fundamental frequency of the current with respect to the load voltage is responsible for the above-mentioned reactive power.

1.3.2 Burst-firing operation

In burst-firing operation, complete sinusoidal cycles of the supply voltage are either switched through to the load or inhibited. In this mode of operation, the power supplied to the load is regulated by the proportion of active cycles, and this proportion is determined by a continuous analog signal from a controlling device, such as an electronic controller.

The proportion (or *duty cycle*) is defined as follows (Fig. 4):

$$\text{Duty cycle} = \frac{\text{ON time } T_e}{\text{Clock period } T} \qquad (1)$$

From this, the power supplied to the load can be derived as $P = P_{max} \cdot \frac{T_e}{T}$

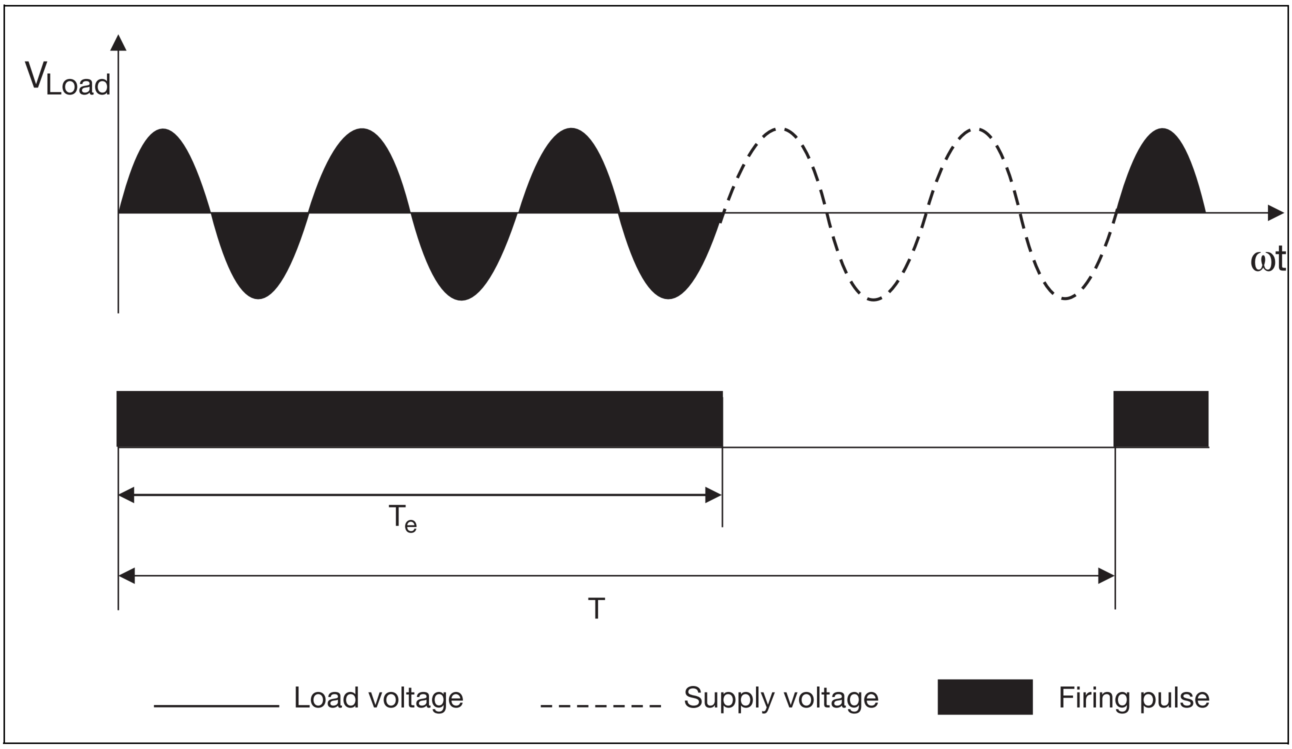


Fig. 4: Burst-firing operation

Thyristor power units from JUMO provide the option of choosing between a fixed clock period of 500ms and a variable clock period. In this second option, the thyristor electronics always uses the fastest feasible clock frequency for the output level that is required.

For instance, a power level of 50 % can be implemented with one full sinewave cycle of current followed by one cycle that is left out. Assuming that the supply frequency is 50Hz, the resulting clock frequency will be 25Hz, corresponding to a 40 ms clock period.

The operational option with variable clock periods is the one that comes closest to phase-angle control, because of the short pulse bursts. Choosing the variable clock period option means that the thyristor power unit can achieve fine regulation of the output power and yet still respond quickly. It is therefore better suited to fast control loops than the option with a fixed clock period.

A fixed clock rate is mainly used with transformer loads or in the master-slave economy circuit (Chapter 5.1.2.3).

When using power units that operate on the zero-crossing principle, care must be taken that only complete cycles of the sinewave are switched.

This is to ensure that there is no resulting DC component, which would cause a very detrimental loading of the supply network or any transformers in the supply feed.

Burst-firing has the following advantages over phase-angle control.

- Since the thyristors are always switched at the zero-crossing point of the voltage (for a resistive load), the generation of RF interference is minimized.
- The load current is purely sinusoidal, so no harmonics are generated.
- As long as purely resistive loads are driven, there is no inductive load on the supply, unlike phase-angle control. There is no lagging reactive current to produce a reactive power.

The disadvantage lies in the fluctuations in the supply voltage that can result from the clocking of the load when the supply feed does not have a sufficiently low impedance. This effect, known as *voltage flicker*, causes unpleasant variations in the light intensity, i.e. flickering, of any lighting installations that are fed from the same supply. Limits for this flickering can be found in the European Standard EN 61 000-3-3.

The switching at the zero-crossing point leads to the *inrush* effect in transformers, whereby the iron in the transfomer core becomes magnetically saturated, with the result that the primary current is then effectively only limited by the resistance of the primary winding. In such a case, the current surge at switch-on can reach something like 50 x the rated current.

In order to be able to obtain the advantages of pulse-burst operation – such as low reactive power – with transformer loads, *burst-firing with cut-back of the first half-cycle* can be used as an operating mode (Fig. 5). The phase control angle for the first half-cycle of a pulse group (burst) – also known as α_{Start} – can be set to a value between 0° and 90°, to achieve optimum matching for the particular transformer that is used.

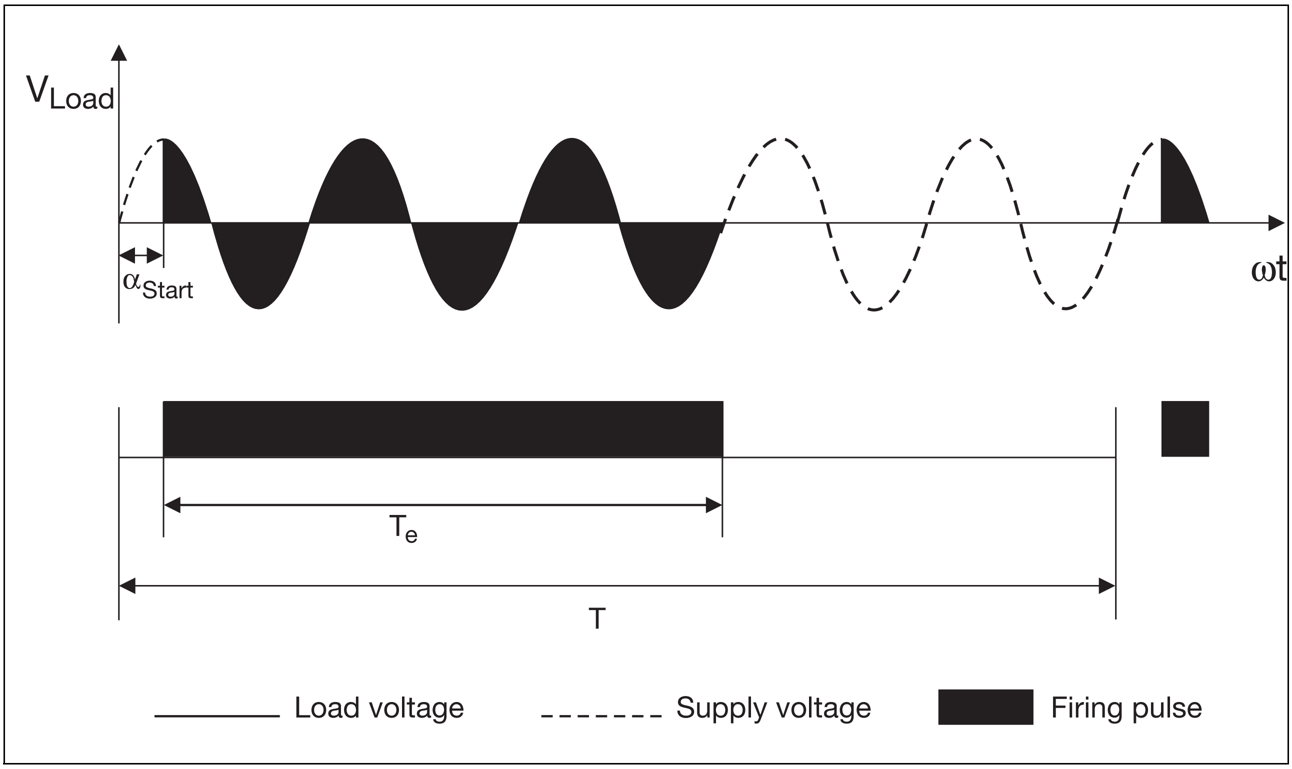


Fig. 5: Burst-firing with cut-back of the first half-cycle of the supply voltage

1.3.3 Burst-firing operation with phase-angle controlled start

This type of operation begins with a soft start under phase-angle control. When this has advanced to a complete half-cycle, the controller switches over automatically to burst-firing operation.

If the thyristor power unit also includes an automatic current limiting function, it will keep running under phase-angle control up to the point where the automatic changeover to burst-firing operation no longer drives the current above the (adjustable) limit. The starting angle α_{Start} for the first half-cycle of each burst can also be adjusted between 0° and 90° for the subsequent operation of the transformer load.

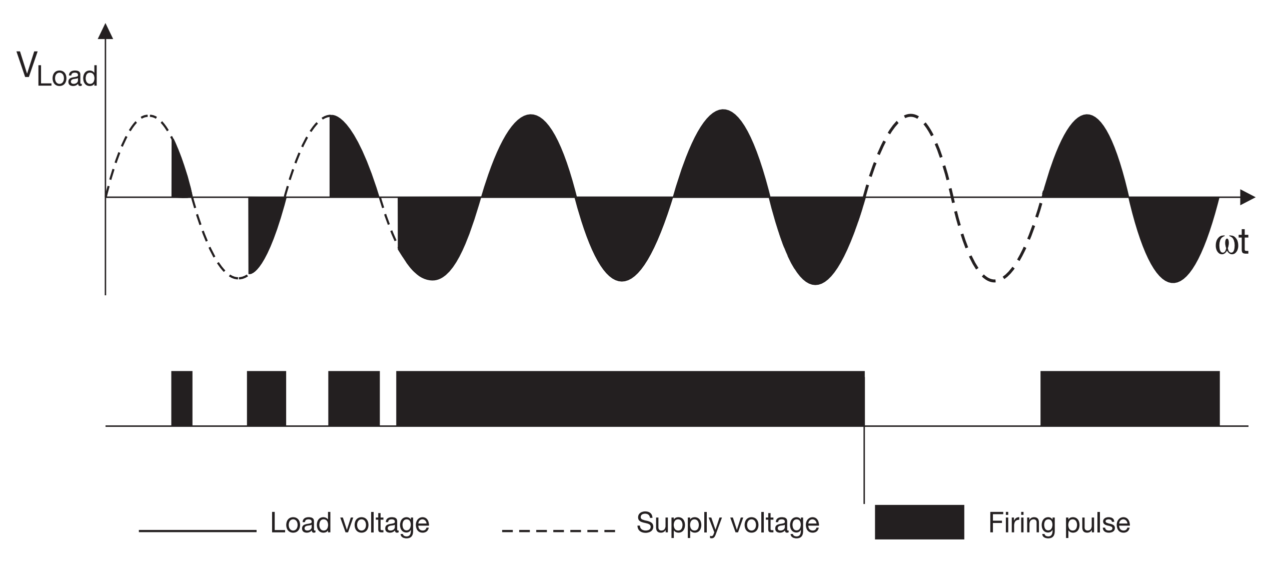


Fig. 6: Burst firing operation with phase-angle controlled start

During burst-firing operation, the maximum OFF time is also monitored. If there is a somewhat longer break between bursts, the thyristor power unit falls back into phase-angle control for a fresh soft start. This type of operation is used for transformer loads or resistive loads that have a strongly temperature-dependent resistance (e.g. $R_{cold} : R_{hot} \approx 1 : 16$ for Kanthal Super heater elements).

2.1 The IGBT as an electronic switch

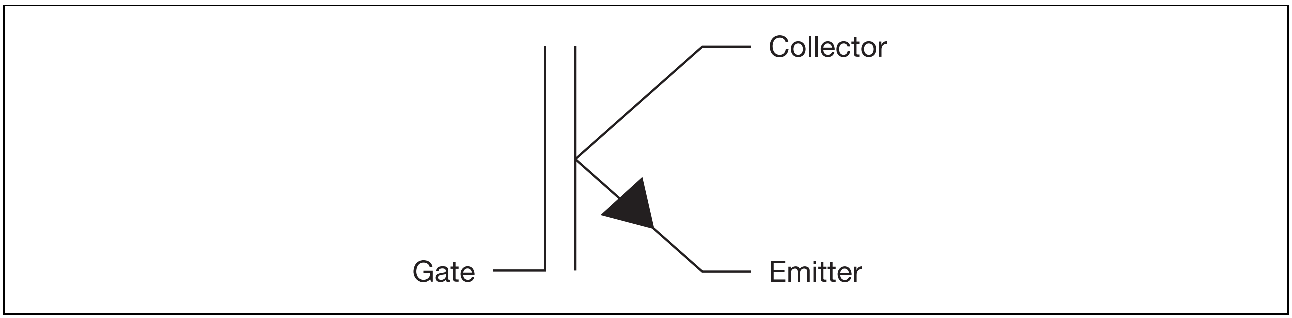


Fig. 7: Circuit symbol for an IGBT

The IGBT (Insulated Gate Bipolar Transistor) behaves like an NPN transistor with an insulated MOSFET gate as the control electrode. The drain of the MOSFET device is accordingly designated as the collector and the source is designated as the emitter. When an IGBT is driven in the forwards direction, the collector-emitter path will become conductive if a positive voltage is applied between gate and emitter. The device is shut off by a negative voltage between gate and emitter, even if a current is flowing between collector and emitter at the time. The IGBT is only used as a switching device, and not as a linear amplifier.

An IGBT has a very high voltage blocking capability, and the saturation voltage (the voltage drop between the collector and emitter when the device is conducting) is comparatively low. It is very easy to control through the gate electrode, and the switching losses are acceptable.

2.2 The IGBT power unit as a control device

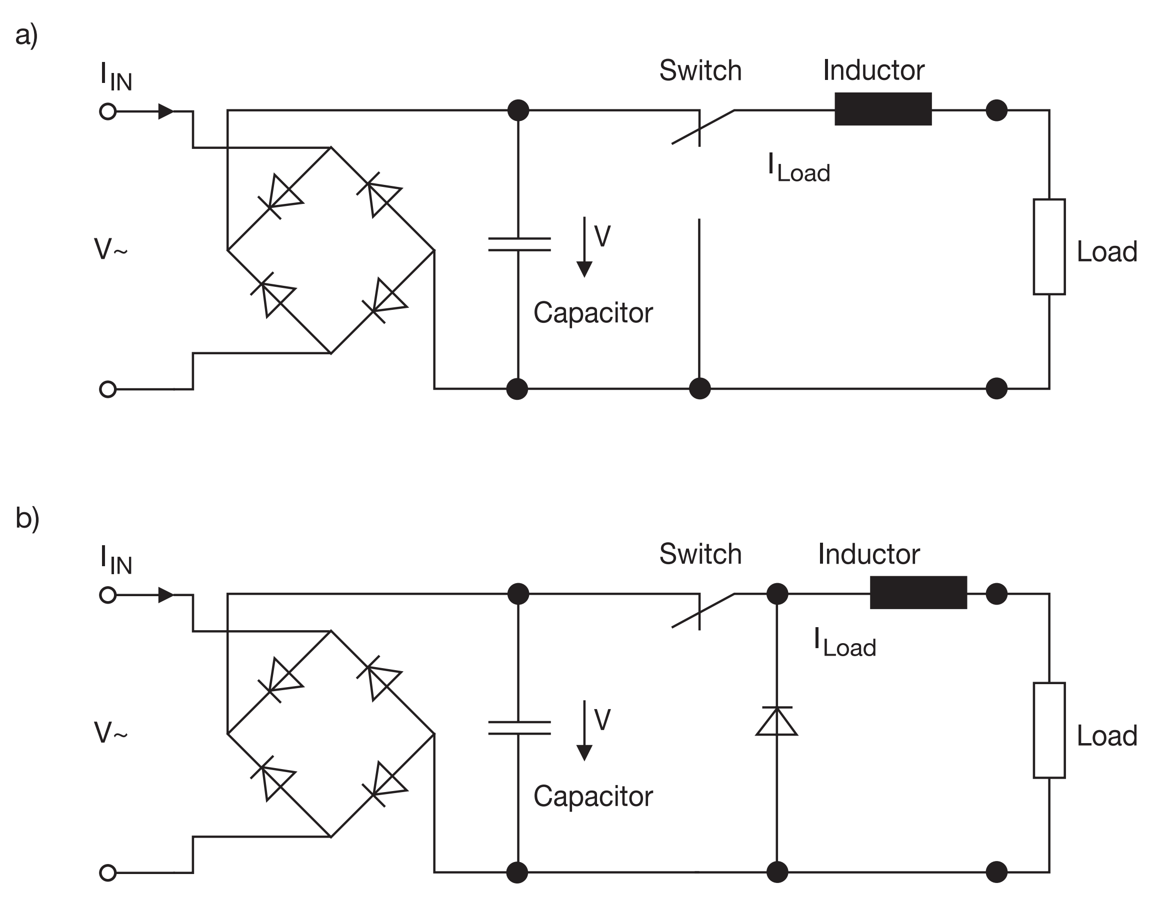


Fig. 8: Basic circuit of an IGBT power unit

The changeover switch shown in Fig. 8 a) can be replaced by a single switch, if a diode is inserted into the circuit as shown in b).

While the switch is closed, the current through the choke rises at a rate that is determined by the value of the inductance. When the switch is opened, the current in the choke continues to flow in the same direction, but now through the freewheel diode. During this period the current falls, until the switch is closed once more. So the ON/OFF ratio for the switch determines the waveform of the load current.
In practice the switch shown in b) is not a mechanical switch, but a semiconductor power switching device such as, in this case, an IGBT.

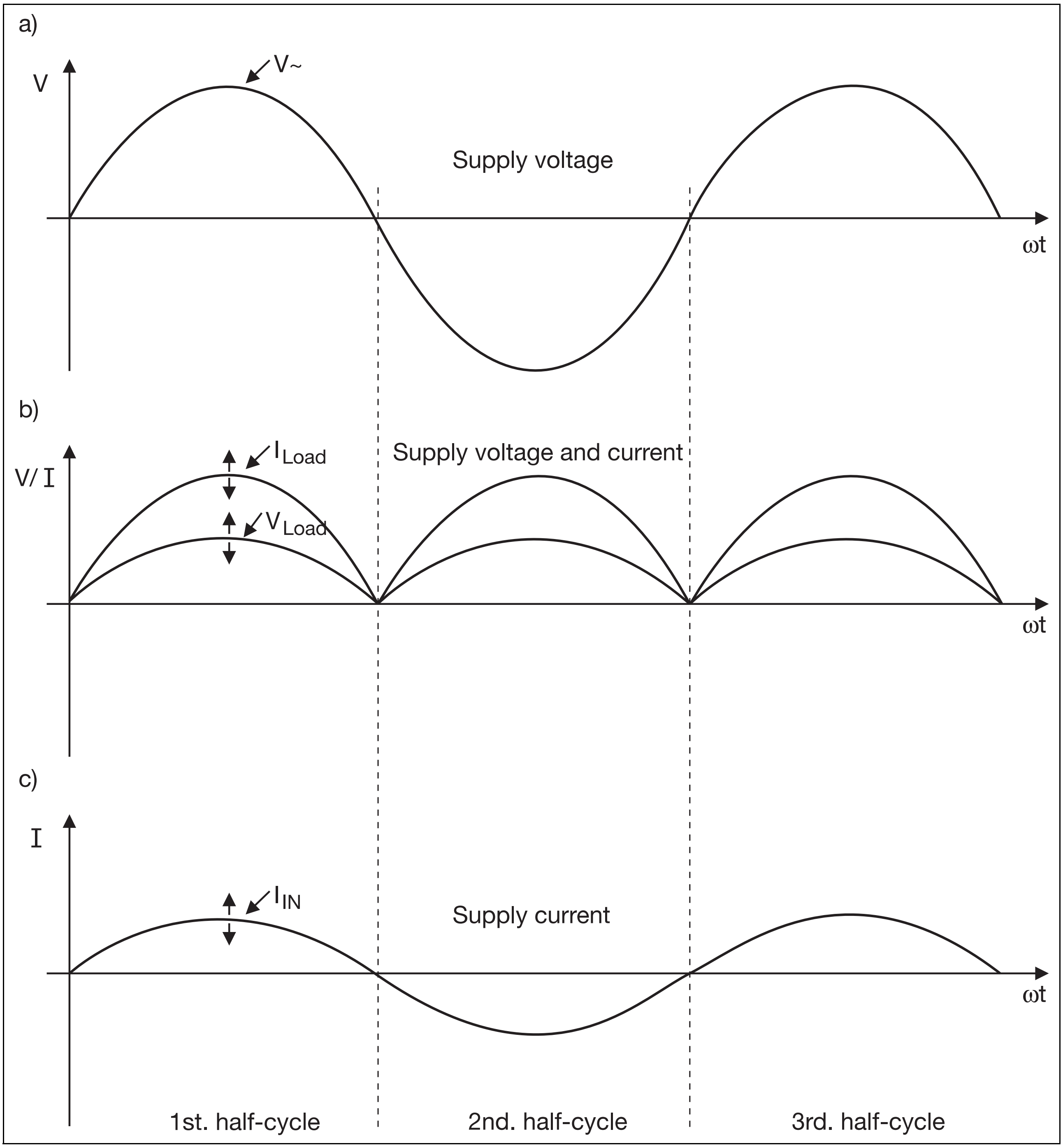


Fig. 9: Supply voltage/current and load voltage/current for an IGBT power unit

The load voltage waveform shown in Fig. 9 b) is an idealized one. In practice, a tolerance band is defined for the intended form of the load voltage waveform and pulse-width modulation is used to keep the actual load voltage within this band. This means that there is a noise signal superimposed on the load voltage, but the level of the harmonics which are produced is relatively low.

The IGBT power unit has only one mode of operation – amplitude control. Put simply, this means that the user (system) generates a control signal (for example, a 0 — 20 mA standard signal) for the set level, and the IGBT power unit produces a pulsed DC output that has an amplitude that is proportional to this control signal. A pulsed DC voltage with an effective value of 230V is indicated as follows: DC230V ≃.

2 IGBT power units

Note: the output voltage has a DC component, so this circuit must *never* be used to drive a transformer load.

The JUMO IPC is a power converter for controlling heater loads that previously required a transformer (either a variable transformer or a combination of transformer + thyristor power unit). It functions in such a way that you can think of it as being effectively an electronic transformer with a pulsed DC output voltage.

It combines the advantages of the normal variable transformer, such as usual amplitude regulation and sinusoidal supply loading, with the advantages of a thyristor power unit, such as current limiting, load monitoring, underlying control loops and so on.

There is no electrical isolation between the (input) supply voltage and the (output) load voltage.

This converter is suitable for all those applications where substantial resistive loads have to be switched. Thanks to the amplitude control (which means that the current drawn from the supply is always sinusoidal), synchronous clock controls (as for burst-firing operation) or power-factor compensation networks (to compensate for phase control reactive power) are not required.

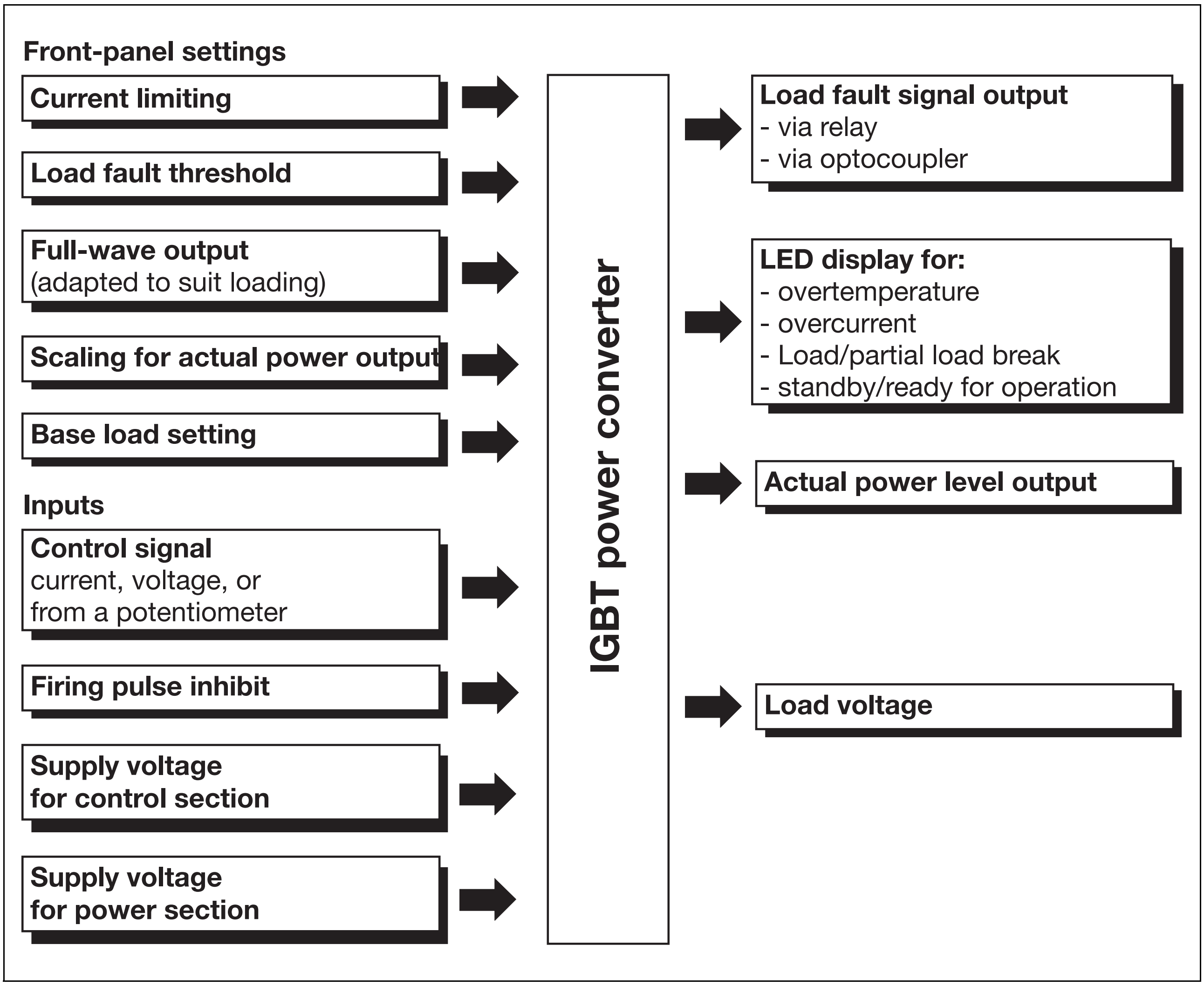


Fig. 10: **Block structure**

Special features of IGBT power units:

- Low interference (flicker) on the electrical supply when operating substantial resistive loads
- Can operate low-voltage heater elements directly from the electrical supply, without needing a step-down transformer
- Minimum harmonic generation in the supply to the equipment, and low weight (no power transformer needed)
- Short-circuit proof during power-on
- Supply current drawn is proportional to the power required (amplitude control)
- Control is independent of the resistance characteristic of the heater elements
- Compensation for the ageing process in SIC heater elements
- Minimum control reactive power
- Compact dimensions
- Free selection of the underlying control loop: V^2, P, I^2

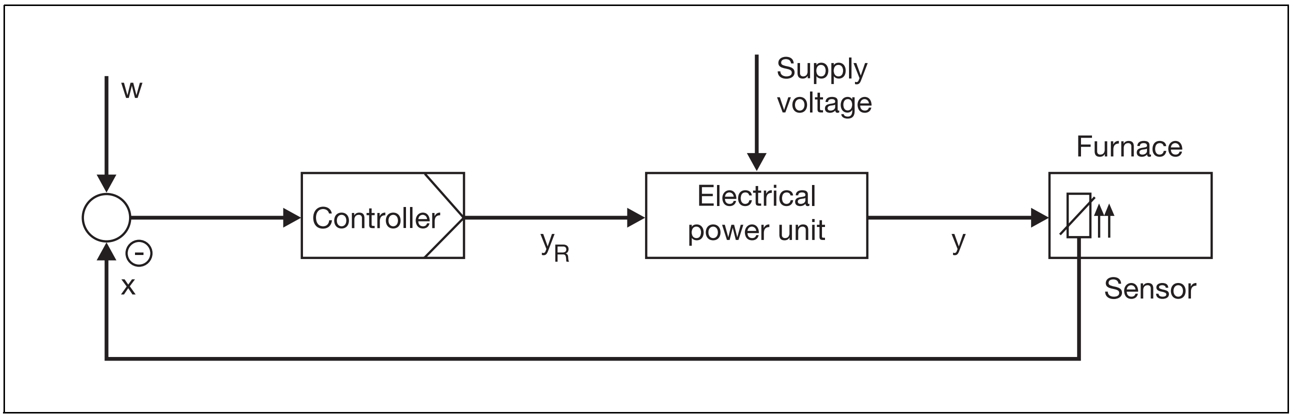


Fig. 11: Control loop using an electronic power unit

In this chapter we will take a look at electrical power units in a closed control loop, using a furnace control system as an example. The electrical supply voltage is connected to the power unit. The controller derives the output level y_R from the difference between the set value (w) for the furnace temperature and the actual (or *process*) value (x) which is acquired by a sensor inside the furnace. The output level can vary over the range 0 — 100 % and is produced as a standard signal output, e.g. 0 — 10 V. The output level signal is fed to the power unit.

The task of the power unit is to feed energy into the heater elements in the furnace, proportional to the controller output level:

- For a **thyristor power unit** using **phase-angle control**, this means that it alters the firing angle over the range from 180° to 0°, corresponding to a controller output level of 0 — 100 %
- If the **thyristor power unit** is using the **burst-firing mode**, it alters the duty cycle T from 0 — 100 % to correspond to the controller output level of 0 — 100 %
- When using an **IGBT power unit**, the amplitude of the load voltage is varied from 0 V to $V_{\text{Load max}}$ to correspond to the controller output level of 0 — 100 %

Now let’s look at the response of the electronic power unit in Fig. 11 to variations of the supply voltage, using the example of a thyristor power unit operating in burst-firing mode:

Assume, for example, that the controller is regulating the thyristor power unit at an output level of $y_R = 50$ %. This means that the power unit is operating with a duty cycle of 50 %, i.e. the supply voltage is switched through to the load for half of the complete sinewaves of the supply voltage. The energy that the power unit is feeding to the load (the furnace) is, say, $y \triangleq 5\,\text{kW}$, and is just that which is needed to keep the furnace at the required temperature (for example, 250°C).

Now assume that the supply voltage sags by 10 %, from 230 V AC to 207 V AC. The thyristor power unit is still being regulated by the output control level of 50 % and so it still has a 50 % duty cycle. But the supply voltage being switched through to the load is 10 % smaller, with the result that the power fed to the furnace is 19 % lower, as can be seen from the following equation:

$$P_{230\,\text{V AC}} - \Delta P = \frac{(V\sim - 0.1 \bullet V\sim)^2}{R} = \frac{(0.9V\sim)^2}{R} = 0.81 \bullet P_{230\,\text{V AC}} \qquad (2)$$

$P_{230\text{V AC}}$: power in the load resistance at a supply voltage V of 230 V AC

ΔP: power reduction resulting from reduced supply voltage

R: resistance of the load

This 19 % reduction in the energy being fed in means that the furnace temperature falls.
A continuing constant temperature is no longer assured. The controller recognizes the deviation through the relatively slow response of the temperature control loop and increases its output level (y_R) until the furnace reaches the original temperature (250 °C) again.

To avoid power variations caused by supply voltage fluctuations, a **subordinate (underlying) control loop** is built into the controller system. This makes an instant correction for variations in the amount of energy provided. The result is that the power unit always provides a power level (y) at the output that is proportional to its input signal (y_R). The principle of an underlying control loop is shown in Fig. 12.

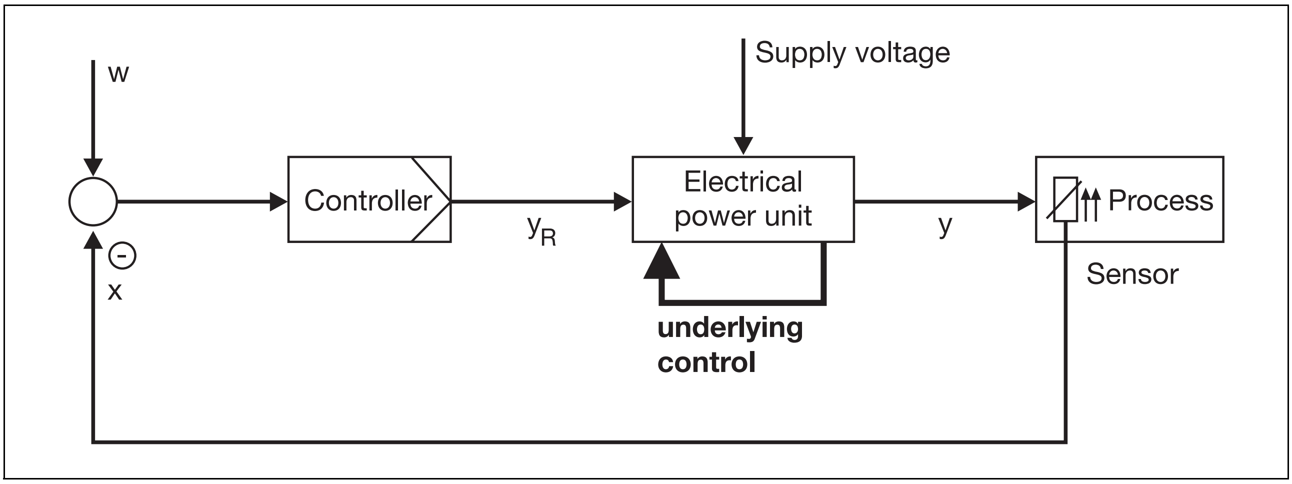


Fig. 12: Underlying control loop: principle

A distinction is made between V^2, I^2 and P control loops. V^2 control is used in most applications. There are however some applications where an I^2 or P control has advantageous control-loop characteristics.
The three different types of underlying control are described in the following sections.

3.1 V^2 control

Considering the power P_{Load} in a resistive load, we know that it is determined by the voltage on the load, V_{Load} and the resistance of load, R, as follows:

$$P_{Load} = \frac{V_{Load}^{\;2}}{R} \tag{3}$$

Equation 3 shows that, for a constant load resistance, the power in this resistance is proportional to V_{Load}^{2}.

$$P_{Load} \sim V_{Load}^{\;2} \tag{4}$$

A power unit with a V^2 control will regulate in such a manner that the square of the load voltage is proportional to the signal input (e.g. 0 — 20 mA) to the unit.

$$V_{Load}^{\;2} \sim \text{Input signal to the power unit} \tag{5}$$

Combining equations 5 and 4, we can see that the power in the load resistance is proportional to the input signal to the power unit.

$$P_{Load} \sim \text{Input signal to the power unit (0 — 20 mA)} \tag{6}$$

Heater elements that have a positive temperature coefficient (TC), i.e. where the electrical resistance increases with increasing temperature, are usually driven from a power unit that incorporates an underlying V^2 control (Fig. 13).

These are resistive materials such as

- Kanthal-Super
- tungsten
- molybdenum
- platinum
- quartz radiators

Their cold resistance is substantially lower than their resistance when hot (by a factor of 6 — 16). These heater elements are usually run at temperatures above 1000 °C.

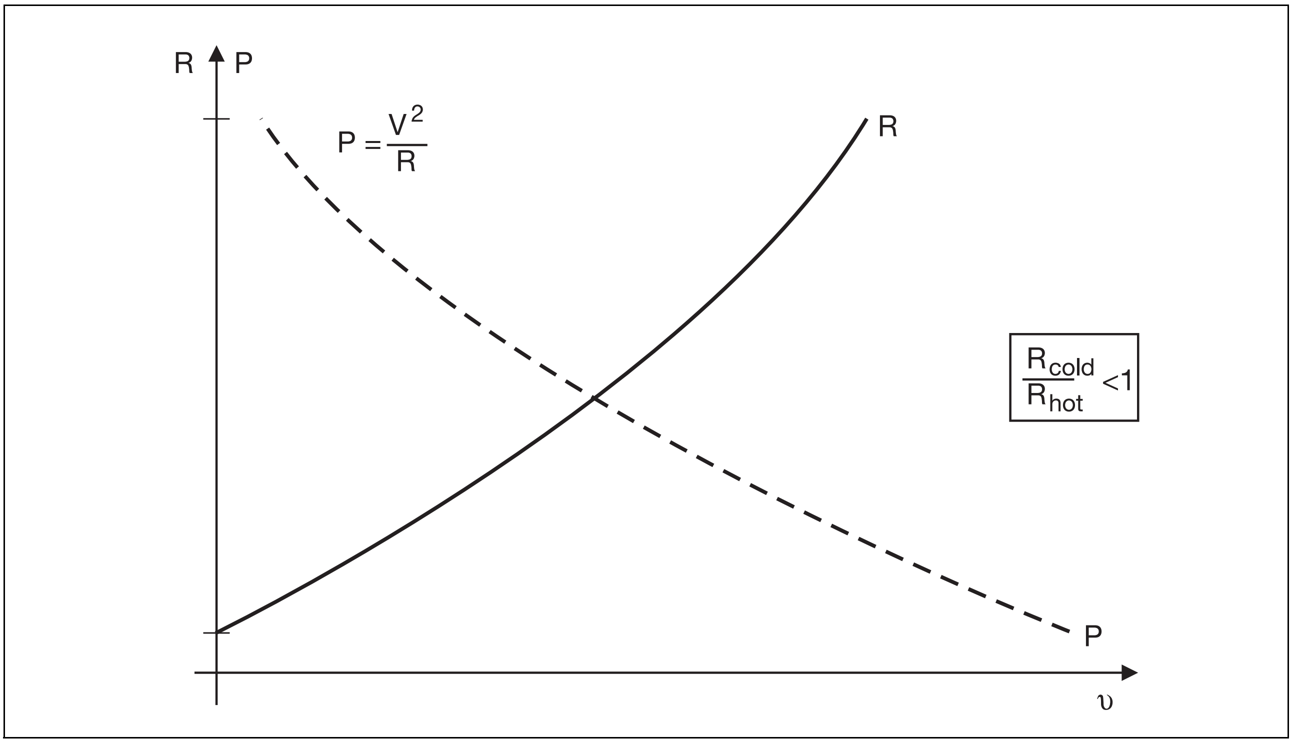


Fig. 13: Heater element with a positive TC

Power units need current limiting for the starting phase. The constant current and the increasing resistance mean that, initially, the power in the heater element increases in proportion to R, since the power $P = I^2 \cdot R$.

When the current falls below the preset limit value, the current limiting is no longer effective, and the power unit operates with the underlying V^2 control, i.e. if the resistance continues to increase, the power fed to the heater elements falls, since the voltage is held constant:

$P_{Load} = \frac{{V_{Load}}^2}{R}$ automatically becomes smaller.

This effect supports the complete control loop. As the furnace temperature rises towards the set value, the power fed to the furnace is reduced (for a given load voltage), so the power unit itself slows the approach to the setpoint value. This damps out any tendency to overshoot the final temperature.

Another application for V^2 control is in lighting systems, where the intensity of the illumination is proportional to V^2.

Some resistance materials have a TC that is close to 1. These include heater elements made from nickel/chrome, constantan etc. These do not place any special requirements on the thyristor power unit (such as current limiting). The resistance characteristic for a heater element with a TC ≈ 1 is shown in Fig. 14.

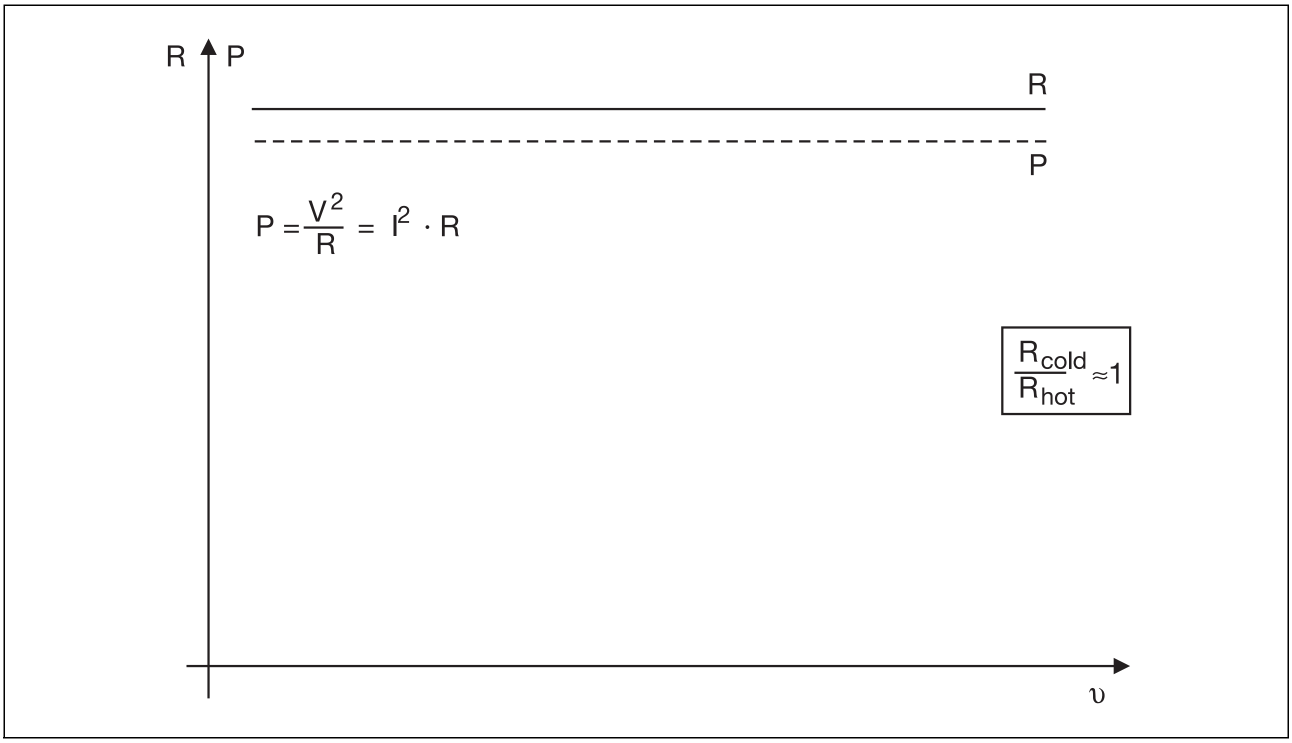


Fig. 14: Heater element with TC ≈ 1

3.2 I^2 control

If we now consider the power P_{Load} in a resistive load, as a function of the load current I_{Load} and the resistance R, the equation is as follows:

$$P_{Load} = I^2_{Load} \bullet R \qquad (7)$$

From equation 7 it can be seen that, for a constant load resistance, the power in the resistance is proportional to I^2.

$$P_{Load} \sim I^2_{Load} \qquad (8)$$

A power unit with I^2 control therefore regulates the square of the load current so that it is proportional to the input signal.

$$I^2_{Load} \sim \text{Input signal of the power unit} \qquad (9)$$

Combining equations 9 and 8, we can see that the power in the load resistance is proportional to the input signal to the power unit.

$$P_{Load} \sim \text{Input signal to the power unit (0 — 20 mA)} \qquad (10)$$

Current control (I^2 control) is advantageous for heater elements with a negative TC, where the electrical resistance becomes smaller as the temperature increases (Fig. 15).

This behavior is shown by non-metallic materials such as graphite or glass melts. Molten glasses are not usually heated by heater elements but by letting a current flow through the melt, so that the electrical energy is converted directly into heat in the molten material. The current is applied through electrodes.

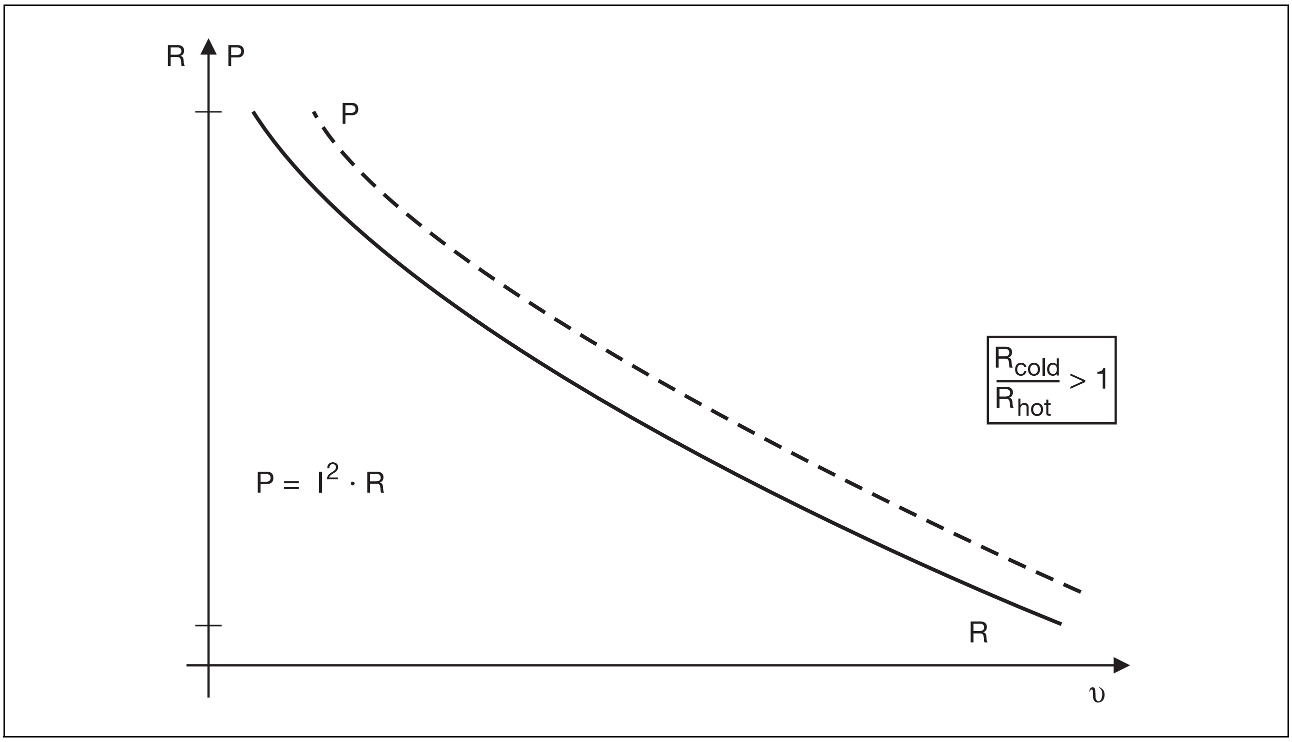


Fig. 15: Heater element with a negative TC

Looking at the power equation $P = I^2 \cdot R$, we can see that an I^2 control has the same regulatory effect on the power as already described for the V^2 control. In other words, by regulating a constant current while the temperature rises, the power in the process is automatically reduced as the resistance falls.

3.3 P control

Power control (P control) is a continuous regulation of the product V · I, the power. In this case, there is a precise linear relationship between the output power and the level of the signal input (e.g. 0 — 20 mA) to the thyristor power unit.

A typical application of this type of underlying control is for regulating heater elements which are subject to long-term drift combined with a temperature-dependent resistance, as is the case with silicon carbide elements (Fig. 16).

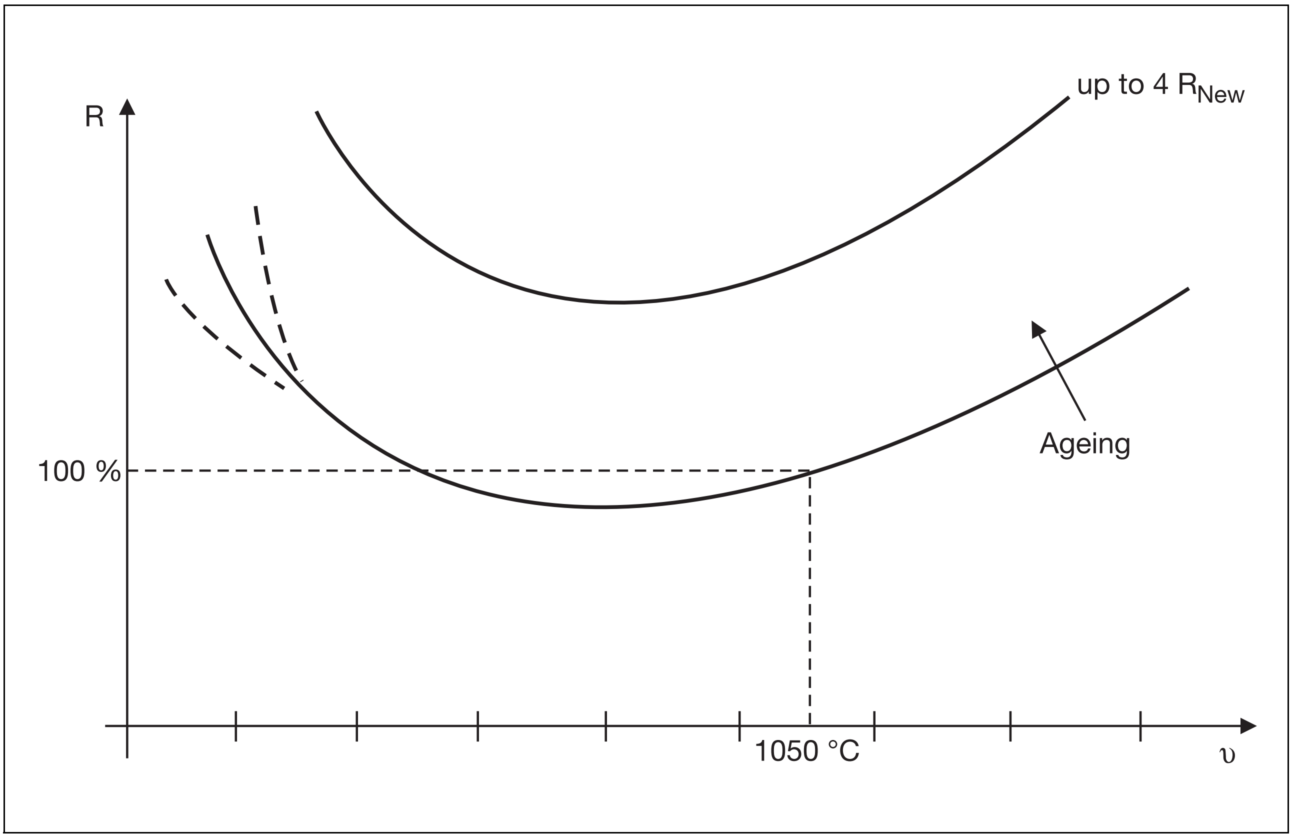


Fig. 16: Resistance changes for silicon carbide

Silicon carbide heater elements have a nominal resistance that can alter by a factor of 4 over the long term. So when dimensioning a system it is necessary to provide power units (whether thyristor or IGBT power units) that can produce twice the (nominal) power for the heater elements.

With **thyristor power units**, care must be taken that they can handle twice the current that is calculated from the power requirements for operating the furnace.

This is explained in detail below. Since the power in the heater elements is supposed to remain constant, in spite of the ageing effect:

(1) $P_{Old} = P_{New} = \text{constant}$

Old ≙ old state of the heater element (after ageing)
New ≙ new condition of the heater element

and, furthermore:

(2) $P_{Old} = V_{Old} \cdot I_{Old}, R_{Old} = \frac{V_{Old}}{I_{Old}}$

(3) $P_{New} = V_{New} \cdot I_{New}, R_{New} = \frac{V_{New}}{I_{New}}$

The relationship between the resistance when new and after ageing is

(4) $R_{New} = \frac{R_{Old}}{4}$

From which, combining with (2) and (3)

(5) $\frac{V_{New}}{I_{New}} = \frac{V_{Old}}{4I_{Old}}$

To fulfil 1) it is therefore necessary that

$$V_{New} = \frac{V_{Old}}{2}, \qquad I_{New} = 2I_{Old} \tag{11}$$

in other words

$$P_{New} = V_{New} \bullet I_{New} = \frac{V_{Old}}{2} \bullet 2I_{Old} = V_{Old} \bullet I_{Old} = P_{Old} \tag{12}$$

The output current of the IGBT power unit is dimensioned for the current consumption of the SiC heating in its new condition.

On the other hand, the load voltage capability of the power unit must have a voltage reserve to cover the compensation for the ageing effect. In the example above this is a factor of 2.

With an IGBT power unit the current drawn **from the supply** is always the sinusoidal current needed to produce the actual power required. It is independent of the varying condition of the SiC heater elements through ageing.

P control is also used for free-running economy circuits running off a 3-phase supply network (see Section 5.1.2.3) or for situations where changes in the load resistance, such as the results of a partial load break, must be compensated by the control system.

The previous chapters discussed thyristor and IGBT power units and their basic functions. But the complexity of industrial and control processes require additional functions, for instance to ensure the reliable operation of the corresponding sections of the installation. This chapter describes some of these functions. These are functions that have been implemented in the JUMO thyristor power unit TYA-110 and the JUMO IGBT power unit IPC, in response to user feedback combined with years of experience in the development of power units. Some of these functions are not included in the standard versions of the equipment, but are available as options.

4.1 Load circuit monitoring

4.1.1 Partial load break

Partial load break detection monitors the load circuit, and is, for instance, useful if several heater elements are wired in parallel (Fig. 17). If an element becomes faulty (open-circuit), the resulting change in resistance is detected by an electronic comparison of current and voltage. The threshold for the indication of a load fault can normally be adjusted by a trimmer.

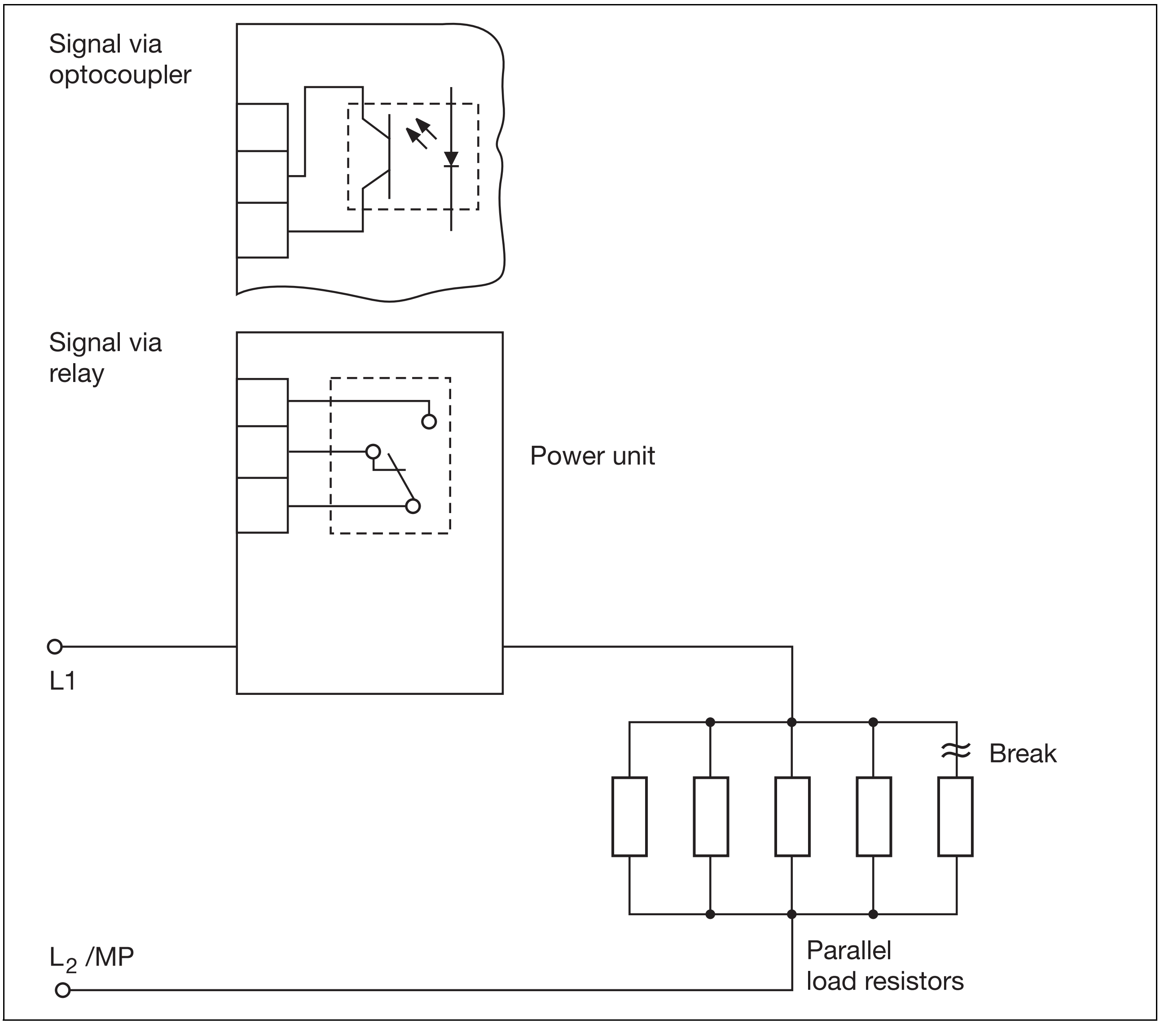


Fig. 17: Monitoring for partial load failure

A fault condition is usually indicated by a corresponding LED on the front panel. A floating relay contact or an optocoupler output is often provided as a signal output.

4.1.2 Overcurrent monitoring

Some power units have an internal switch for the option of changing over to overcurrent monitoring instead of partial load (undercurrent) monitoring. This option makes it possible to monitor a number of heater elements that are in a series circuit for a possible short-circuit of one or more elements.

4.2 Controlling power units

Power units can be controlled either by a continuous current signal (e.g. 0 — 20mA) or a continuous voltage signal (e.g. 0 — 10V). It is often possible to connect an external potentiometer to provide the setting level for the output.

Power units are normally controlled by control devices with a continuous output (DC current or voltage). Standard signals are, for example, 0 — 20mA, 0 — 5V, 0 — 10V or the “Live-Zero” signals 4 — 20mA, 1 — 5V, 2 — 10V.

4.2.1 Implementing a base load

Some thermal processes must not be allowed to cool down to the ambient temperature, and so there must always be some electrical energy fed into the system. This is achieved by setting a base load. The base load (for example, 33% of the total power) is then always fed into the load system, even when there is no control signal from the preceding controller. The size of the base load is usually set by an internal potentiometer or by a signal on a control input.

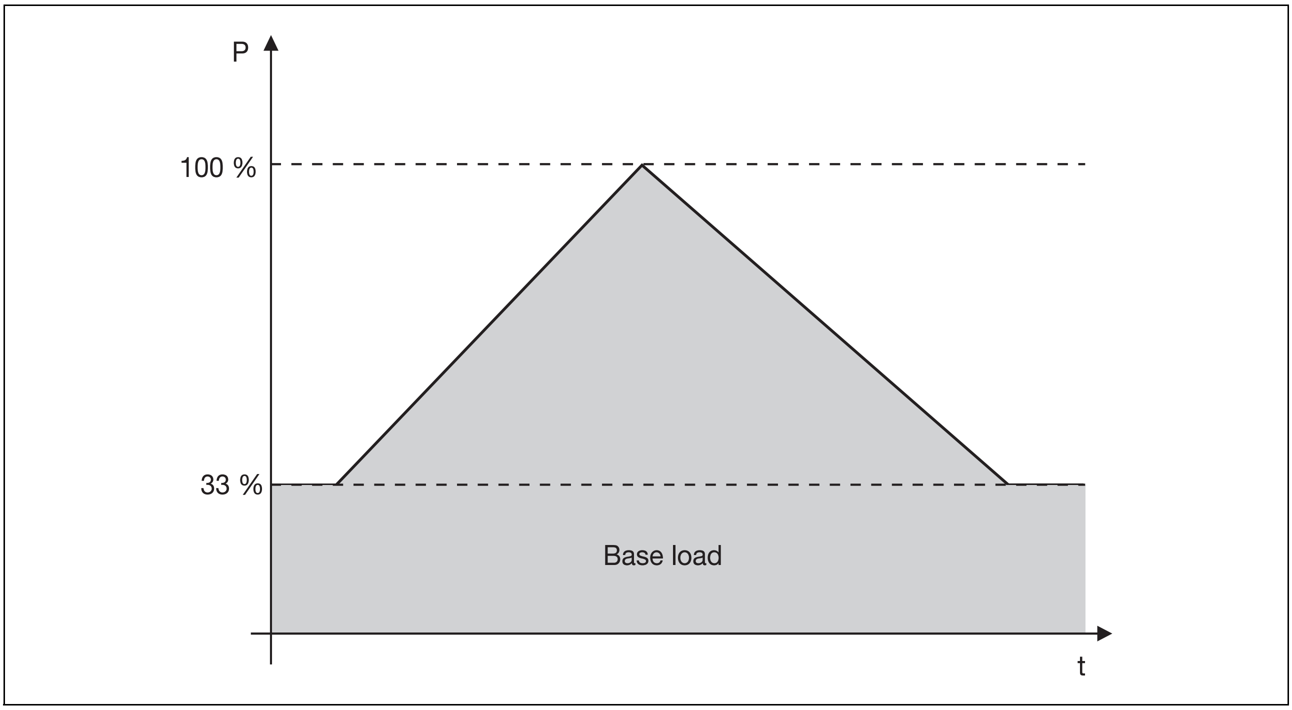


Fig. 18: Representation of a base load

The potentiometer is used to set the base load, and the analog (continuous signal) input is used to control the remaining range from the base load up to the maximum output level (Fig. 18).

4.2.2 Input signal attentuation

This function is used to reduce the maximum power output of the power unit, and so to adjust the power output to match the output signal from the preceding controller.

The setting is made by first of all setting the controller to provide a 100 % output level to the power unit (for instance, 10V or 20mA). The power output from the power unit is now reduced (usually by a potentiometer on the power unit) until it produces the maximum power that is actually required.

4.3 Soft start

The soft start function ensures that the power unit does not suddenly apply a high power to the load when the system is switched on. The power applied to the load is gradually increased from 0 to the set value. This function provides increased operational safety with transformer loads, since the transformer is gradually magnetized and can then be operated at full power ⇒ the inrush effect is avoided.

For **thyristor power units** in **phase-angle control**, the soft start is implemented by starting with the load switched to the supply at a phase angle completely cut back to α=180° and then gradually advancing the phase angle.

If the thyristor power unit is configured for **burst-firing mode**, then the first half-cycle of the sinewaves are also initially cut back and then advanced to a firing angle of 0°. The following bursts are then switched through completely (see 2.3.3).

The **IGBT power unit** alters its output level by varying the amplitude of the current or voltage. In this case, the soft start is implemented so that if there is a step change of the set level at the input to the power unit, the corresponding amplitude is gradually increased from 0 to the output level that corresponds to the set value.

4.4 Current limiting

Current limiting is indispensible for heater elements that have a hot resistance R_h that is several times larger than the cold resistance R_c (such as Kanthal-Super elements, where $\frac{R_h}{R_c} \approx \frac{15}{1}$).

With V^2 control, which is appropriate for these elements, the load current would be impermissibly high when the elements are cold (the same would occur with P control). In practice, the maximum permissible effective current is set by a trimmer, and an LED indicates when the power unit runs into current limiting.

Thyristor power units only have a current limiting in phase-angle control: if the unit runs into current limiting the phase angle is not advanced any further.

IGBT power units clamp the amplitude of the output current if they run into current limiting.

4.5 Inhibit input

An appropriate signal on this logical control input prevents the output of the unit from providing any power. In **thyristor power units** this is done by simply not firing the thyristors from the next half-cycle on. In an **IGBT power unit** a negative voltage is applied to the gate electrodes of the IGBTs. In effect, this instantly shuts off the collector-emitter path. When the unit is enabled again, by the external contact, the unit restarts through the soft start function.

However, if a power system has to be electrically disconnected, then a contactor or main switch must be wired in series with the supply input, as otherwise a very low current (leakage current) will still flow through the semiconductor components (thyristors or IGBTs).

4.6 Actual power level output

Power units often have a signal output to indicate the actual level of the power output. This can then generate a standard signal output to indicate the level of the power unit output (as V^2, I^2 or P).

4.7 External mode changeover for thyristor power units

External mode switching is the option (for a thyristor power unit) of changing over from burst-firing mode to phase-angle control by closing an external contact. This will automatically activate the soft start function and current limiting, provided that they are configured in the instrument. The power unit will now remain in the phase-angle control mode for as long as the external contact is kept closed. When the contact is opened, the unit falls back automatically into burst-firing operation, unless this is prevented by activation of the current limiting.

5 Power units on single/3-phase supplies

In the following chapter we will take a look at using power units on single and 3-phase supplies. The basic data of the heater elements, rated voltage and rated current, will also be used as aids for the dimensioning of the power units.

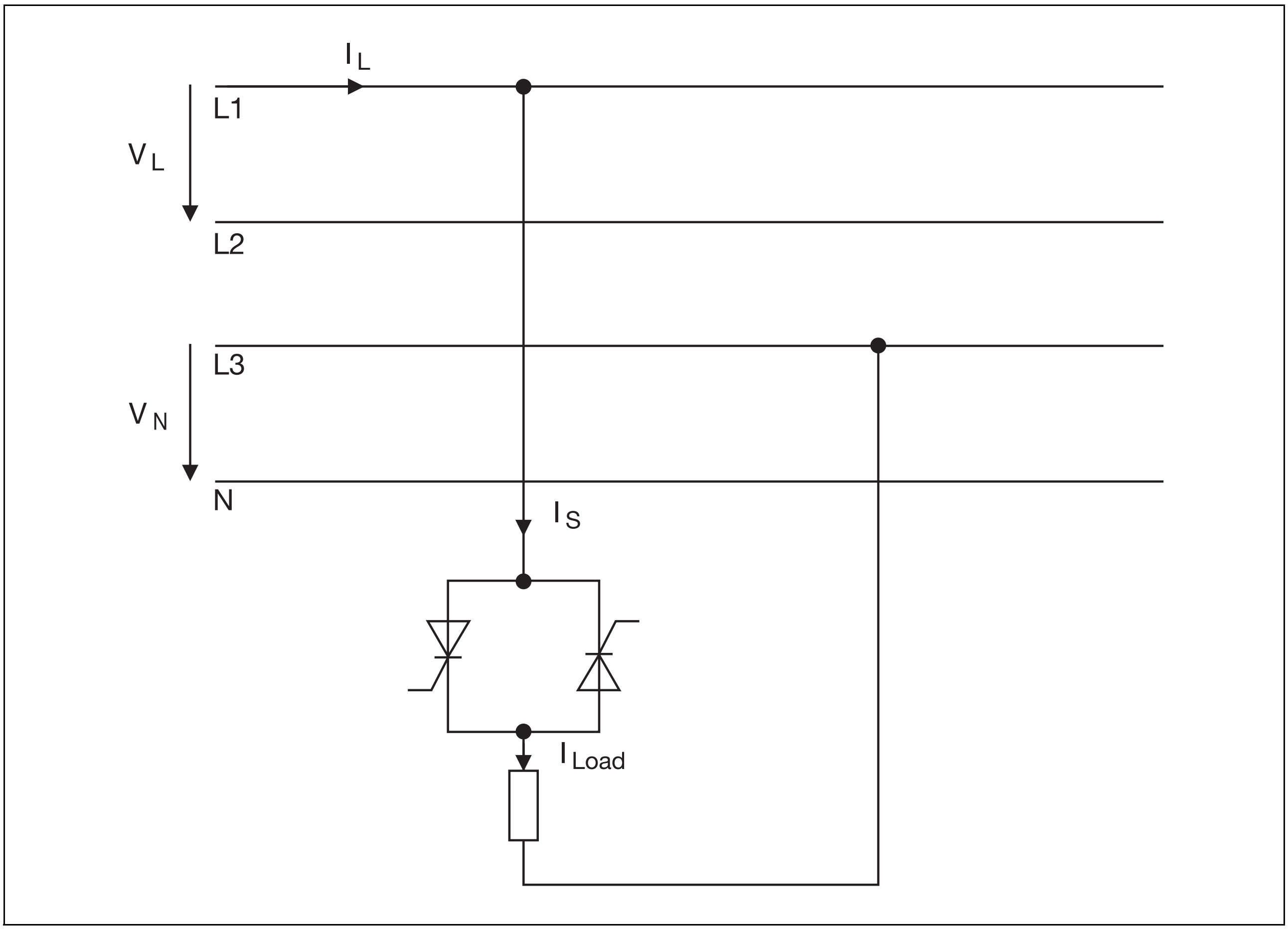


Fig. 19: Parameters in a 3-phase system

We will begin by defining a standardized nomenclature for currents and voltages in a 3-phase system (Fig. 19):

V_N: phase voltage (voltage between the phase and neutral conductors)

V_L: phase-phase voltage (voltage between two phases)

I_L: current in a phase

I_S: current through the power unit

I_{Load}: load current

Note:
In a three-phase supply network 3~/N/400/230V, the phase-phase voltage is 400V and the phase voltage is 230V.

We will also be using the following abbreviations in this chapter:

$P_{nom/Load}$: nominal (rated) power of the load(s)

$V_{nom/Load}$: nominal voltage for the load(s)

$I_{nom/Load}$: nominal current in the load(s)

5 Power units on single/3-phase supplies

5.1 Thyristor power units on single/3-phase networks

The most important parameters for a thyristor power unit are the rated load voltage and the load current. The importance of these parameters becomes clear if we look at single-phase operation (Fig. 20).

5.1.1 Single-phase operation: phase-N or phase-phase

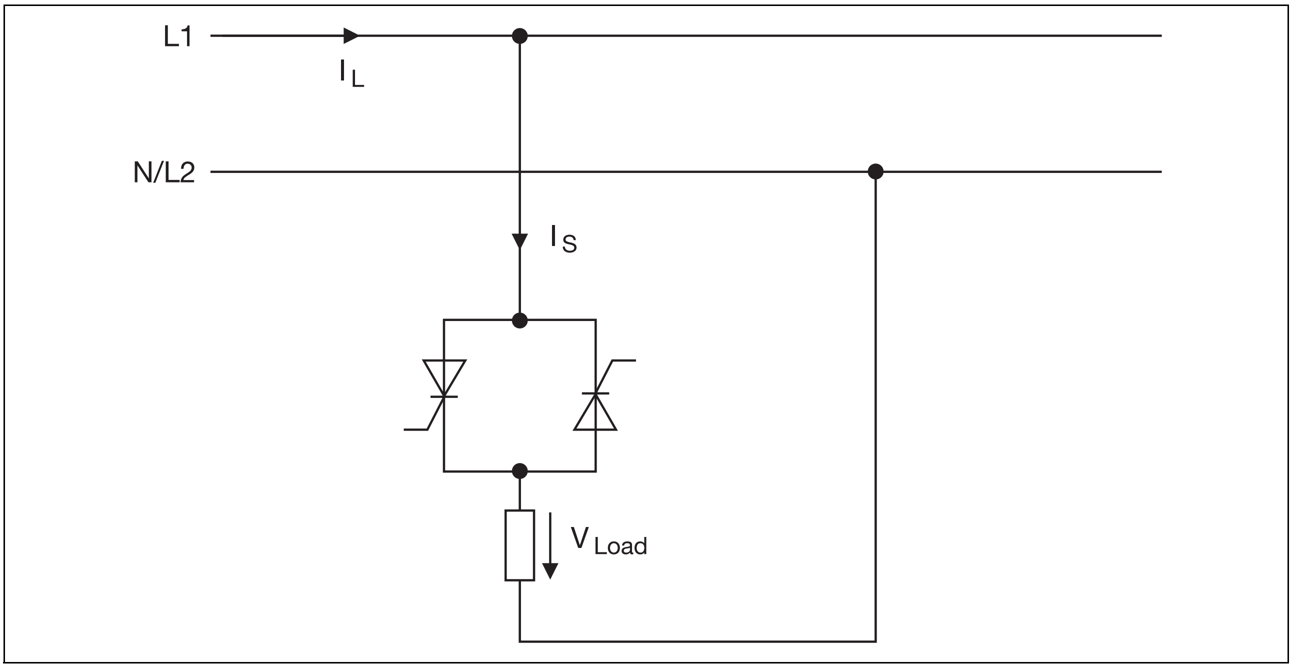


Fig. 20: Single-phase operation (phase-N or phase-phase)

Fig. 20 shows a thyristor power unit in single-phase operation. If the unit is connected between phase and neutral, then the voltage on the power unit, and hence the load, is the single-phase voltage. If the power unit is connected between two phases, then the phase-phase voltage will be applied to the load. The rated voltage of the thyristor power unit must correspond to the phase-neutral or phase-phase voltage of the supply.

We can use Ohm's Law to calculate the load current in the heater elements from the nominal voltage ($V_{nom/Load}$) and the nominal power ($P_{nom/Load}$). The permissible load current I_S of the thyristor power unit must be at least as high as the nominal current in the heater element.

Load connected phase-phase (400V):

$$I_S = \frac{P_{nom/Load}[W]}{V_L} \qquad I_L = I_S \tag{13}$$

Load connected between phase and neutral (230V):

$$I_S = \frac{P_{nom/Load}[W]}{V_N} \qquad I_L = I_S \tag{14}$$

5.1.2 Power units in a 3-phase system

3-phase controls are often assembled from three individual single-phase instruments. This section describes the possible circuit options.

5.1.2.1 4-wire circuit (star configuration, with accessible neutral point)

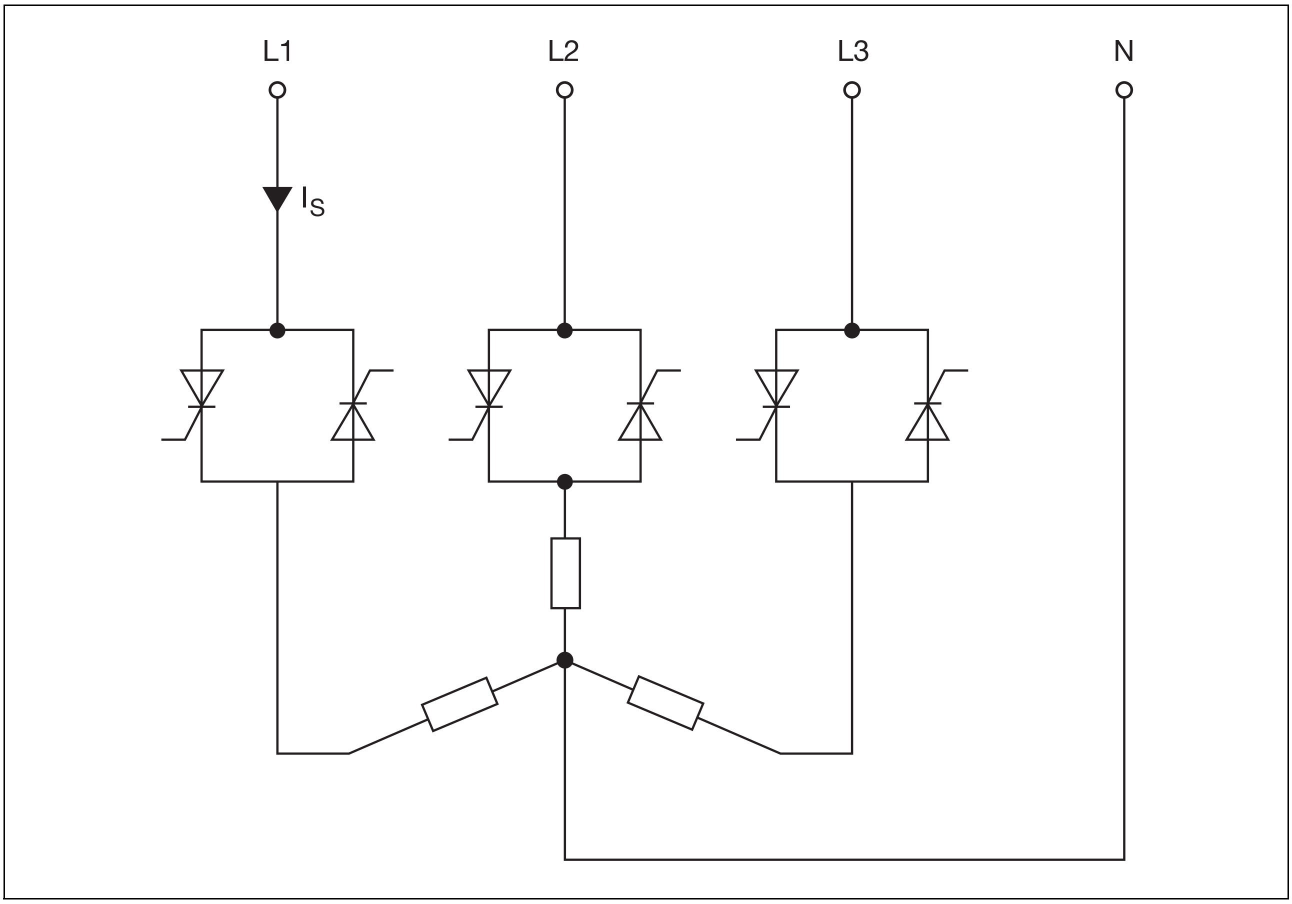


Fig. 21: The 4-wire circuit

Each thyristor power unit switches its phase voltage V_N through to the corresponding section of the load. This means that the units must be selected so that each unit has a nominal load voltage that is at least as high as the phase voltage. The nominal load current that must be provided by each unit is calculated as follows:

$$I_S = \frac{P_{nom/Load}[W]}{3 \bullet V_N} \qquad V_S = V_N \qquad (15)$$

Note: as already defined, $P_{nom/Load}$ is the sum of the three partial loads.

When using this circuit, unfavorable circumstances such as a blown fuse, faulty heater element, assymetrical loading or phase-angle control can cause a current to flow in the neutral conductor N. In particular, using phase-angle control with current limiting and at firing angles $\alpha \geq 60°$ (e.g. 90°) can cause a current in the neutral lead that is twice the current in an individual phase.

5.1.2.2 The 6-wire circuit (open delta configuration)

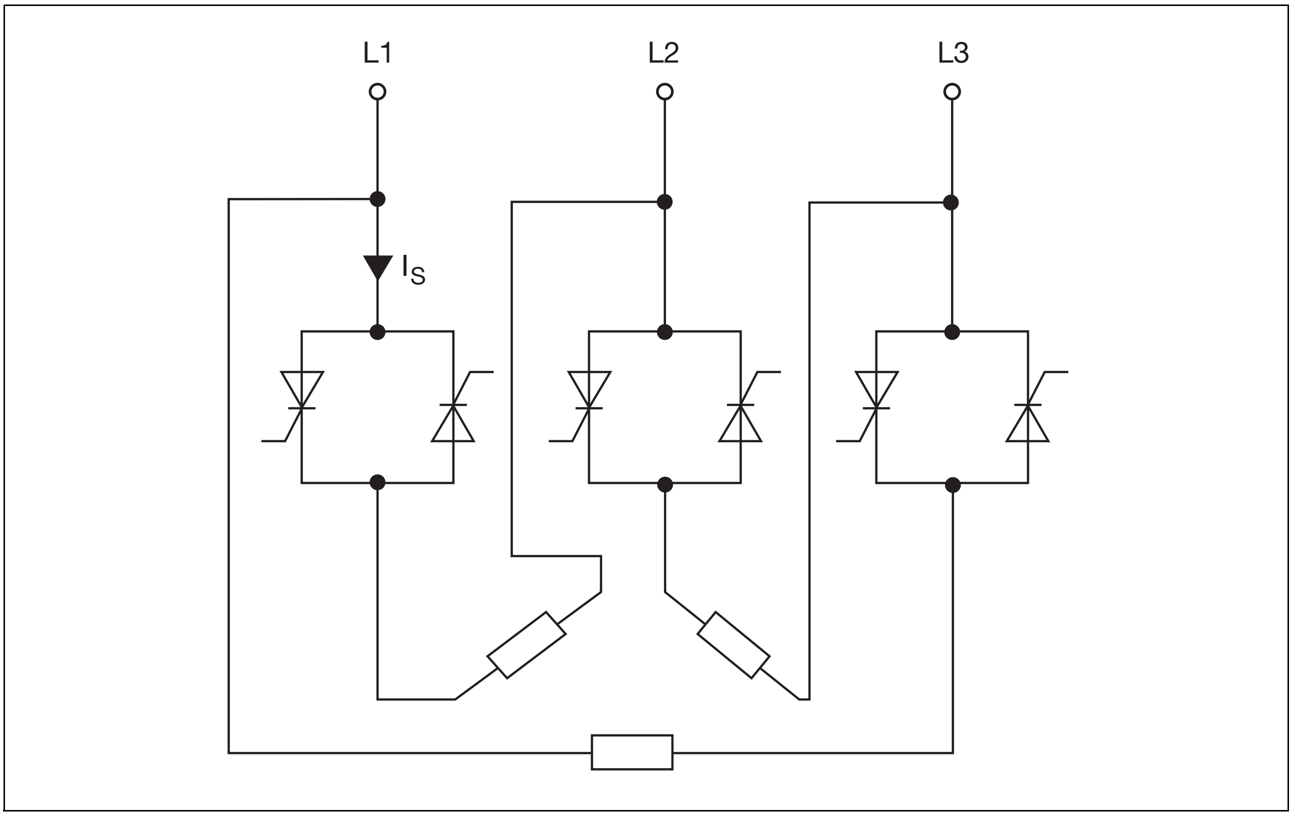


Fig. 22: The 6-wire circuit

In a 6-wire circuit the thyristor power units are wired together with the load sections to form a delta configuration. This circuit too can be used in burst-firing or phase-angle modes of operation.

The phase-phase voltage V_L is present across each thyristor power unit and its load section, so each unit must be selected for a rated load voltage at least as high as the phase-phase voltage. The nominal load current that each unit must provide is calculated as follows:

$$I_S = \frac{P_{nom/Load}[W]}{3 \bullet V_L[V]} \qquad V_S = V_L \tag{16}$$

5.1.2.3 Economy circuits

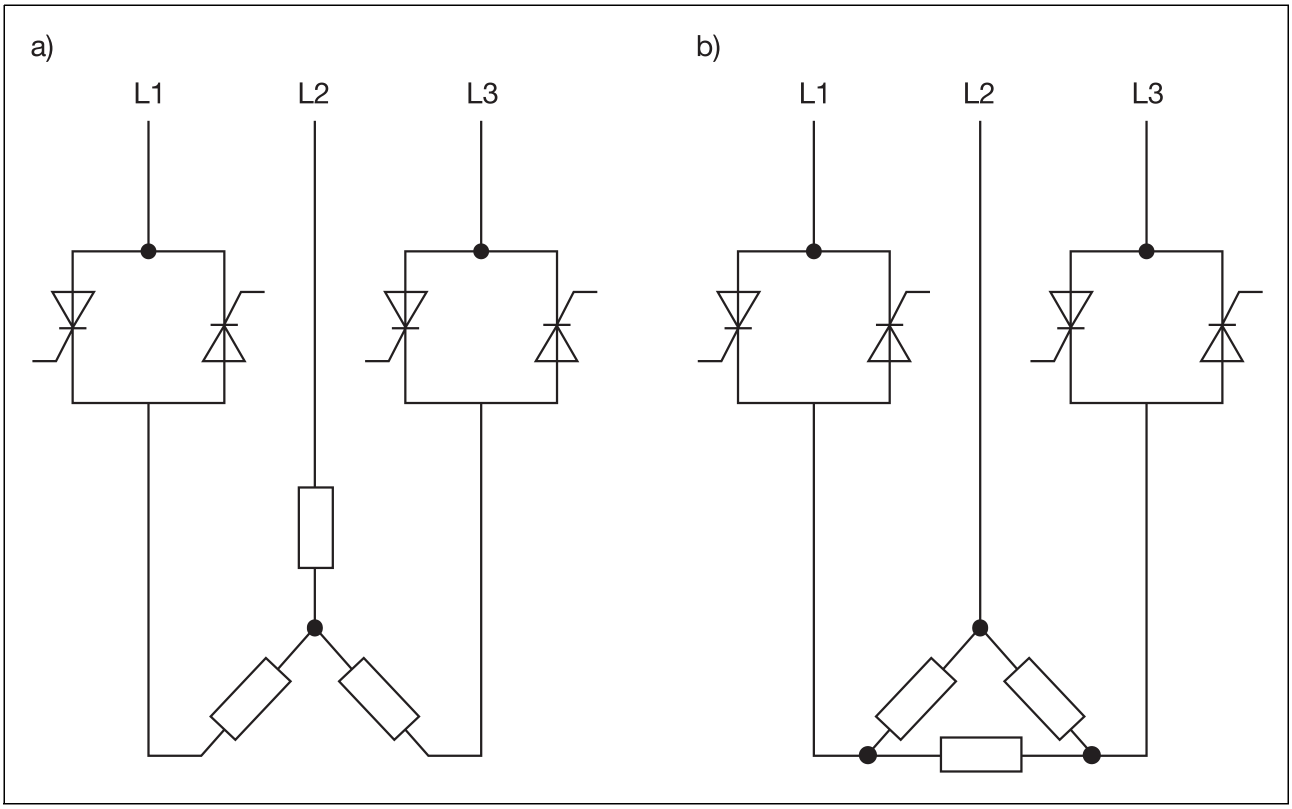


Fig. 23: Economy circuit for loads in star a) and delta b) configurations

In a 3-phase system without a neutral point it is possible to use 2 single-phase thyristor power units to put together what is known as an **economy circuit**, thus saving the 3rd thyristor power unit. The load (in star or delta form) is driven through thyristor power units connected to phases 1 and 3. Phase 2 is connected directly to the load (Fig. 23).

Regardless of whether the load is connected in a star or a delta configuration, the thyristor units must always be dimensioned for the phase-phase voltage.
The thyristor power units must also be operated in burst-firing mode.

There are two principal ways of controlling an economy circuit:

In a **master-slave economy circuit** the control electronics in the master unit takes on the control and regulation function, letting the slave be clocked in synchronism. Used together with a fixed clock period, V^2 control and a load in delta configuration, it is possible to achieve good voltage regulation for the individual load resistors, even with a partial load break. An example that can be mentioned here is application in automatic baking ovens (for pizzas, pancakes and similar).

The master-slave version offers the possibility of clocking transformer loads. The firing point for the first half-cycle of the supply (α_{Start}) can be set between 0° and 90° on the master unit. When using a transformer load it is also advisable to activate the soft start function for the first burst at switch-on. V^2 control should be chosen as the underlying control type. Although the economy circuit operates with only two thyristor units on a 3-phase supply, partial-load break detection can still be implemented without restrictions. This function is, however, usually offered as an option.

The **free-running version of the economy circuit** on the other hand must be operated with a P control. Both power units receive the same signal from the controller and regulate the required power output.

The power units fire their thyristors independently, and so not necessarily simultaneously. This means that the power is not always equally distributed among the 3 load resistors (even if they have the same value of resistance). This type of circuit can therefore only be considered for applications in which a continuously symmetrical load distribution is not required. If a partial load break should occur, it has no direct influence on the temperature stability of the control loop.

This circuit cannot be used for transformer loads.

The rated current for the thyristor power unit in the circuits described above must be at least

star configuration

$$I_S = \frac{P_{tot}[W]}{3 \bullet V_N[V]} \tag{17}$$

or

delta configuration

$$I_S = \frac{P_{tot}[W]}{\sqrt{3} \bullet V_L[V]} \tag{18}$$

5.1.2.4 Table for dimensioning thyristor power units in 3-phase systems

The following table should be helpful in dimensioning the currents, voltages and power levels for thyristor power units in a 3-phase system. The **shaded fields** show the corresponding formulae for a 3-phase supply 3~/N/400/230V.

	Circuit				
	2-wire L1/L2	2-wire L1/N	4-wire	6-wire	3-wire star/delta-economy circuit
No. of power units	1	1	3	3	2
Rated load voltage for thyristor power unit	V_L	V_N	V_N	V_L	V_L
3~/N/400/ 230V	400V	230V	230V	400V	400V
Formula for current in thyristor power unit	$I_S = \frac{P_{nom/Load}}{V_L}$	$I_S = \frac{P_{nom/Load}}{V_N}$	$I_S = \frac{P_{nom/Load}}{3 \bullet V_N}$	$I_S = \frac{P_{nom/Load}}{3 \bullet V_L}$	$I_S = \frac{P_{nom/Load}}{3 \bullet V_N}$
3~/N/400/ 230V	I_S(A) = 2.$P_{nom/Load}$(kW)	I_S(A) = 4.35$P_{nom/Load}$(kW)	I_S(A) = 1.45$P_{nom/Load}$(kW)	I_S(A) = 0.83$P_{nom/Load}$(kW)	I_S(A) = 1.45$P_{nom/Load}$(kW)
Formula for maximum power	$V_L \bullet I_S$	$V_N \bullet I_S$	$3 \bullet V_N \bullet I_S$	$3 \bullet V_L \bullet I_S$	$3 \bullet V_N \bullet I_S$
P_{max} with 3~/N/400/ 230V and I_S = 150A	60kW	34kW	103kW	180kW	103kW

5.2 IGBT power units on single/3-phase networks

For IGBT power units, the most important parameters are the supply voltage for the control section, the supply voltage for the power section, the load voltage and the load current. The significance of these parameters will become clearer if we look at single-phase operation (Fig. 24).

5.2.1 Single-phase operation: phase-N or phase-phase

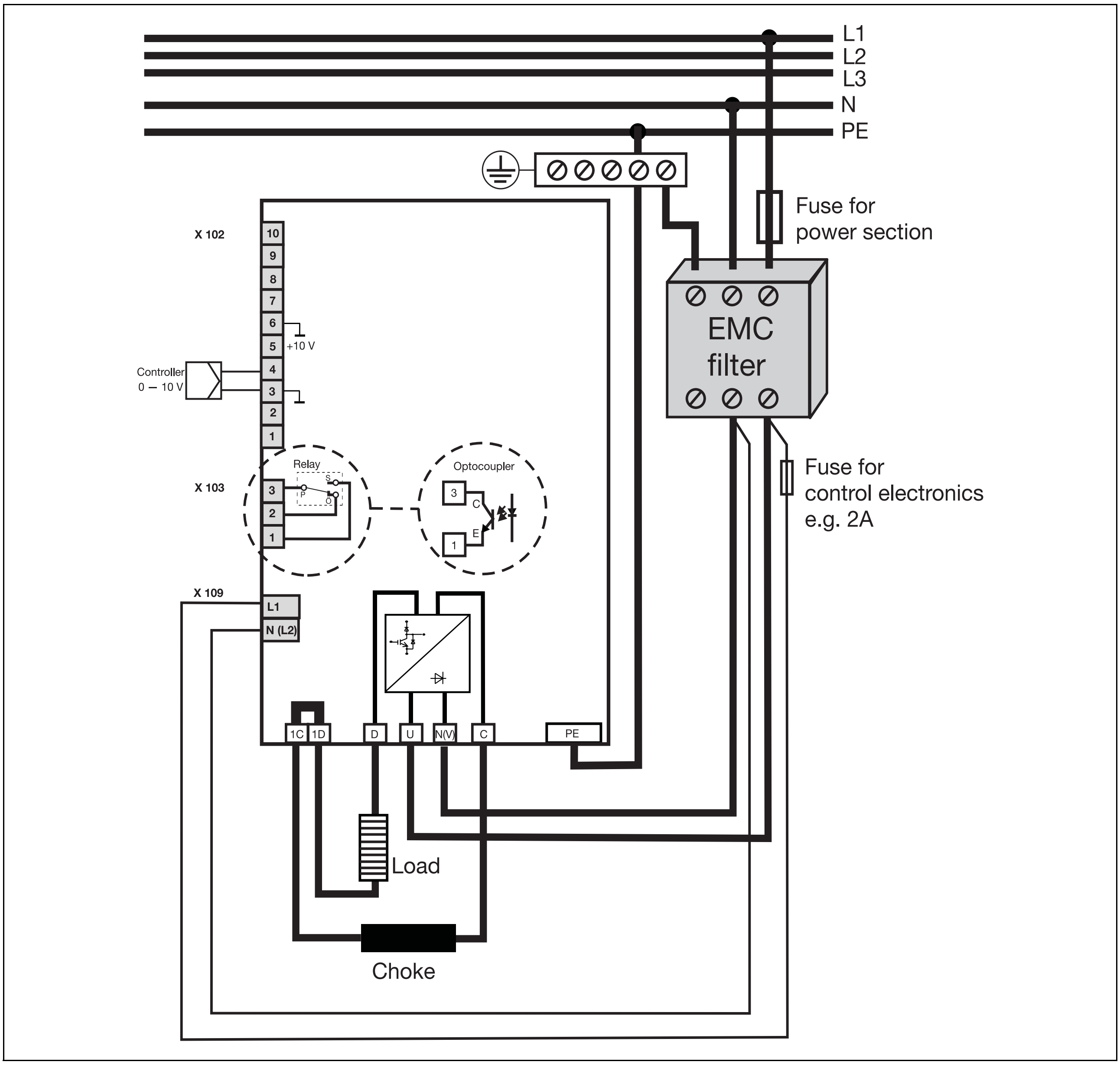


Fig. 24: Single-phase (phase-N) operation of an IPC

Fig. 24 illustrates single-phase operation of the IGBT power unit type IPC. Before an IGBT power unit is used it is necessary to check its specifications: supply voltage for control section, supply voltage for power section, load voltage, and the permissible load current. In Fig. 24 both the control and power sections are run off the phase voltage. The IGBT is operated in such a manner that the rectified sinewave voltage is applied to the load, which is wired between terminals 1D and D, and the amplitude of this voltage can be altered by a control signal between terminals 3 and 4 of X102.

When using an IGBT power unit the current drawn from the supply is not the same as the current in the load. If we neglect the losses in the power unit, the maximum input (supply) current can be calculated as:

$$I_{IN} = \frac{P_{nom/Load}[W]}{\text{Supply voltage to power section}} \tag{19}$$

The maximum load current is given by

$$I_{Load} = \frac{P_{nom/Load}[W]}{\text{Load voltage}} \tag{20}$$

Example: a heater element with a power rating of 5000W and a nominal voltage of 120V AC is driven by an IGBT power unit that has a 230V AC supply to the power section.

The current through the heater element is:

$$I_{Load} = \frac{5000\ W}{120\ V} = 41.7\ A \tag{21}$$

But the current that is drawn from the supply is:

$$I_{IN} \approx \frac{5000\ \ W}{230\ V} = 21.74\ A \tag{22}$$

5.2.2 IGBT power units on 3-phase supplies

IGBTs can also be used in a 3-phase system, to achieve symmetrical loading of all three phases. The circuit layout for this is quite simply 3 x single-phase sections (phase-N or phase-phase) connected to the individual phases of the 3-phase supply.

6 Filtering and interference suppression

To suppress RF interference, such as is generated by thyristor power units operating with phase-angle control, the electrical equipment must be fitted with interference suppression devices.

The control electronics of JUMO power units meets the EMC requirements of EN 61 326.

However, electrical modules such as thyristor or IGBT power units do not have any purpose by themselves. They provide a function as part of a complete system or installation. For this reason, the manufacturer of the complete system or installation must provide suitable filters to suppress interference from the power section of the power units.

There are a number of specialist companies that provide appropriate ranges of filters to deal with any interference problems. Such filters are usually provided as complete modules, ready to be wired into the system.

7 Abbreviations

i_{Th1} = current through thyristor 1
i_{Th2} = current through thyristor 2
I_{Old} = current through an old heater element
I_{New} = current through a new heater element
I_L = current in a supply phase
I_{Load} = load current
I_{IN} = current in supply
I_{Load} = amplitude of the load current
I_S = current through the power unit
P_{Old} = power in an old heater element
P_{Load} = power in the load
P_{New} = power in a new heater element
R_C = cold resistance of a heater element
R_h = hot resistance of a heater element
T_C = temperature coefficient (heater elements)
V_{Old} = voltage on an old heater element
V_N = phase-N voltage
V_L = phase-phase voltage
V_{Load} = load voltage
$V_{Load\ max}$ = maximum load voltage
V_S = load voltage of the power unit
$V_{\sim}$ = supply voltage
$V_{pk\sim}$ = peak amplitude of the supply voltage
W = set value (setpoint)
x = actual value
y = output level
y_R = controller output level
α = phase angle
α_{Start} = firing angle for 1st half-cycle in burst-firing mode
ωt = phase angle at time t

7 Abbreviations