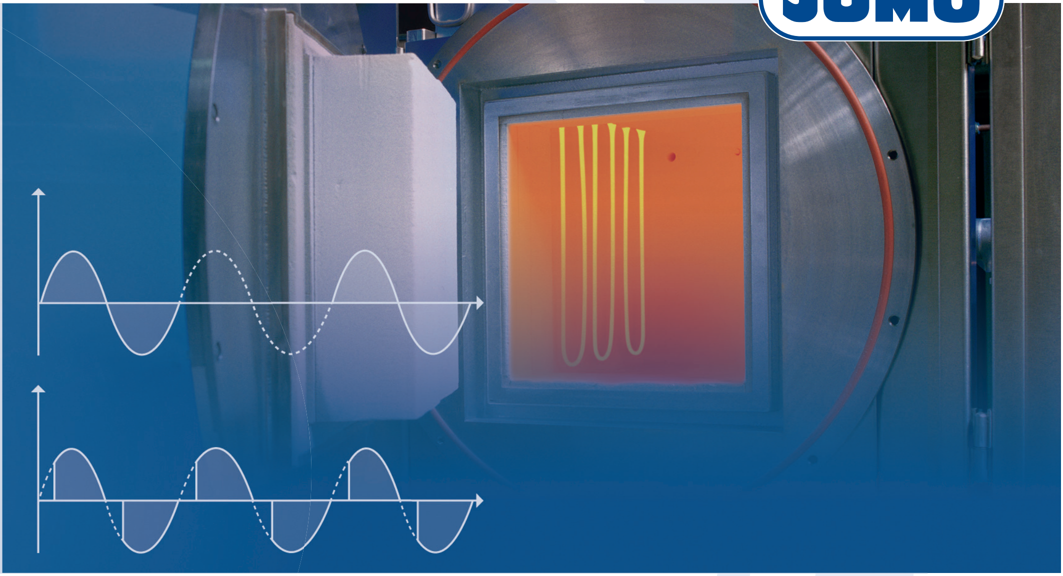

Actuators for Electric Heating

Thyristor power switches, thyristor power controllers, and electronic transformers

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Preface

Electric heating is used in industry and in laboratories for example when there is a need to reach high temperatures, or when the furnace atmosphere has to be extremely pure. Due to the growing need to protect our climate, this form of heating has become increasingly important, as electric energy can be produced without releasing CO_2.

Depending on the requirements, either thyristor power switches or thyristor power controllers are used in electric heating. Electronic transformers or, alternatively, thyristor power controllers with a traditional transformer are used in the operation of high-temperature elements.

This book is designed to help readers select the appropriate type of actuator and provides useful information on how to use them.

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1 An overview of actuators for electric heating

All of the actuators covered in this book are designed for heating using electrical energy. They require **alternating voltage** for the voltage supply and they are actuated in the control loops of temperature controllers. The actuators supply electrical power to heating elements in proportion to the output signal of the temperature controllers.

Thyristor power switches are sufficient for simple applications. They switch the voltage supply to the heating elements whenever the output signal of a two-state controller is activated.

Thyristor power controllers are used for more complex applications. In these actuators, the respective thyristor can be fired in each half wave and the current flow turns off when passing through zero. Thyristor power controllers are used when current limiting or a subordinate control loop is required, for example. They are actuated by means of a continuous controller.

The nominal voltage of silicon carbide heating elements (SiC) or molybdenum disilicide heating elements ($MoSi_2$) does not usually correspond to the mains voltage. These elements can also be operated using thyristor power controllers, but in this case the output voltage of the power controllers is provided via a transformer. The **JUMO IPC 300 electronic transformer** is an advantageous alternative option for operation. In this case, the actuator is also actuated by means of a continuous controller.

1.1 Thyristor power switches

Thyristor power switches are used for contactless switching of alternating current loads. In contrast to mechanical relays, the contacts do not wear when they are switched, and can be frequently switched without any issues.

The heating elements that are to be supplied usually have a nominal voltage at the level of the voltage supply of the low-voltage network (230 V AC for 1-phase operation, or 400 V AC for 3-phase operation in the networks 3/N/400/230 V AC). The switches can be used for switching a wide range of mains voltage (for example AC 42 to 600 V_{eff}).

The mains voltage is supplied to the usually ohmic load (heating element) via the thyristor power switches:

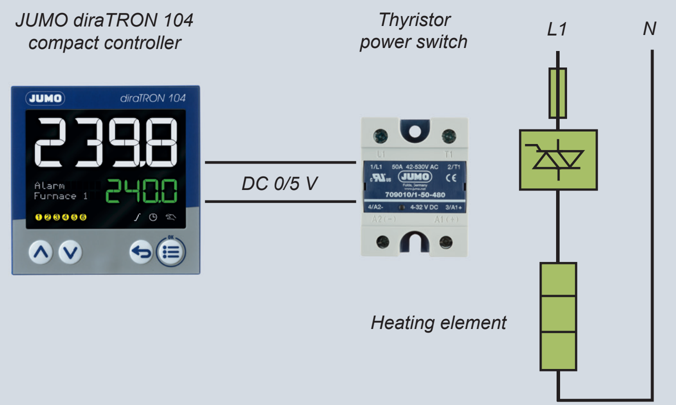


Figure 1: Thyristor power switch with controller and heating element

The power switches have 2 thyristors connected in an antiparallel manner for switching through the positive or negative mains voltage half wave to the load. The voltage supply is switched through as long as the voltage level at the logic input is "high." The logic signal is usually provided by a two-state controller, and the high level is defined for a very high voltage range (for example DC 4 to 32 V; DC < 3.8 V LOW level).

The switches operate as zero voltage switches: the voltage is switched when passing through zero, irrespective of the time when the control signal changes. This prevents network disturbances:

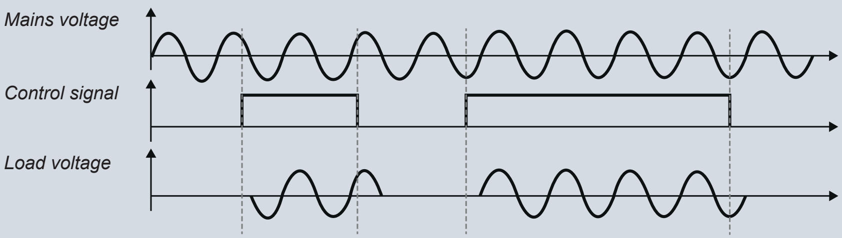


Figure 2: Thyristor power switch: mains voltage, control signal, and load voltage

The 1-pole switches can be used to switch 1-phase loads between the phase and the N-conductor and between 2 phases (Figure 3a). If the N-conductor is not connected in the case of the 3-phase loads, 2 of the 1-pole switches (Figure 3b) are sufficient to operate them. 3-pole versions of the switches are also available (Figure 3c).

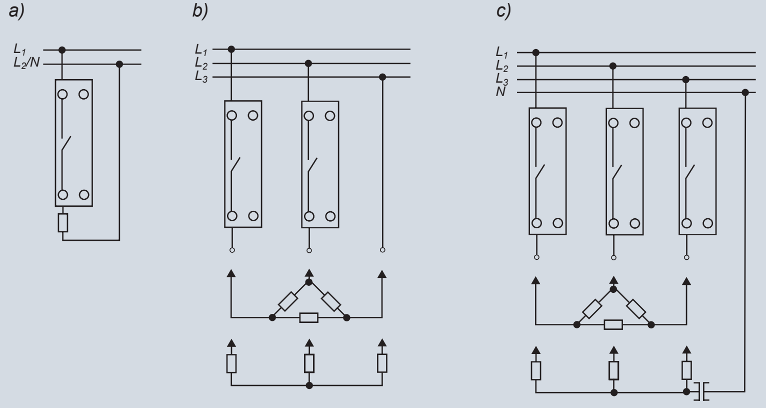


Figure 3: Operation of 1-phase and 3-phase loads with thyristor power switches

The actuators give the maximum possible power or no power to the heating elements. However, the superordinate two-state controllers activate the control signal in a pulse-width modulated manner. For example, for an output level of 50 %, the control signal is activated for 100 ms and deactivated for 100 ms. On average, half of the thermal energy is produced at the heating element. If the "cycle time" is selected sufficiently low on the temperature controller, the control behavior is similar to that for continuous actuation in the case of correspondingly slow control processes.

1.2 Thyristor power controllers

Thyristor power controllers also have 2 thyristors connected in an antiparallel way. In extreme cases, actuation is carried out in every mains voltage half wave (every 10 ms in 50-Hz network), which enables the energy to be dosed very finely.

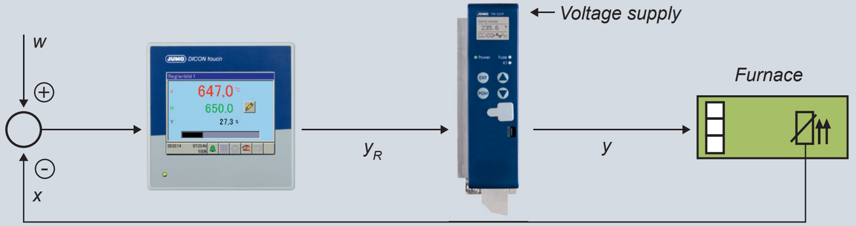


Figure 4: Closed control loop, consisting of a furnace, JUMO TYA 201 thyristor power controller, and JUMO DICON touch process controller

The thyristor power controller displayed in Figure 4 is for 1-phase operation and is actuated by a continuous controller. According to the setpoint value (w) and the furnace temperature (x), the controller has an output level y_R (0 to 100 %). The output level is supplied to the thyristor power controller via a standard signal (usually 4 to 20 mA), and the signal represents the setpoint value for the thyristor power controller. The power controller adjusts the required power at the heating element according to the setpoint value.

Thyristor power controllers in **burst-firing operation** and in **phase-angle operation** are used for varying the electrical power for the heating element. Burst-firing operation is the preferable option, in which the power controllers only switch part of the mains voltage full waves to the load – like for pulse width modulation and thyristor power switches.

If the setpoint value for the thyristor power controller is 60 % for example (Figure 5), 3 mains voltage full waves are switched to the load and 2 full waves are locked:

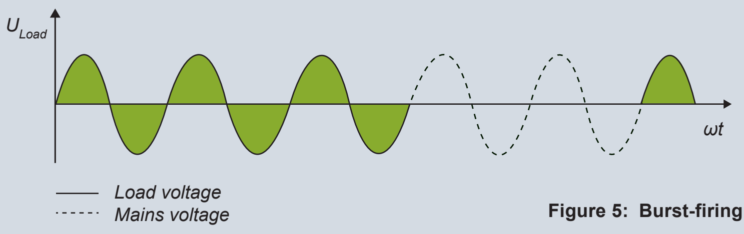


Figure 5: Burst-firing operation

Switching 60 % of the mains voltage full waves (Figure 5) results in 60 % of the maximum possible power being provided. Only complete sine waves are ever switched through. In addition to mains interference, a DC component is thus also avoided (this is important when operating heating elements via transformer).

If the setpoint value is 50 %, accordingly a mains voltage full wave is switched to the load and a sine wave is locked.

Burst-firing operation is unproblematic in contrast to phase-angle operation. Among other uses, it is often used for commonly used metallic heating elements which have a slightly positive temperature coefficient. However, the cold resistance of the elements is not so low that it would result in impermissibly high currents when powering up the system.

The only disadvantage of this mode of operation is that mains voltage fluctuations occur with large loads and weakly dimensioned supply lines. This effect, known as voltage flicker, leads to unpleasant variations in the light intensity of any lighting installations that are connected to the same network.

In **phase-angle operation**, the thyristors are fired during each half wave. This working method is compulsory if current limiting is required. Current limiting is necessary for PTC resistors such as molybdenum disilicide heating elements. These elements have such a low cold resistance that, without current limiting, the flow of current would be impermissibly high when powering up the system.

Furthermore, the fast cycling in phase-angle operation provides the prerequisite for a high standard of temperature control in extremely fast systems. One example is drying plants for print media, in which infrared radiators are used to dry paper webs as they pass through at a fast pace.

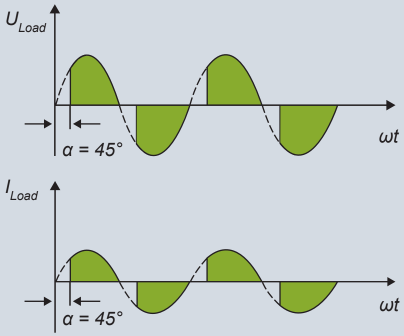


Figure 6: Load voltage curve and load current curve when actuating a resistive load in phase-angle operation

Figure 6 shows an example of a load voltage curve and load current curve in phase-angle operation. The phase angle (ωt) indicates the current position on the sine wave; it is shown on the x-axis. Once a sine wave is completed, the angle is 360° el. (electric) and the next sine full wave begins. The angle for the first half wave is in a range between 0 and 180° el.

In each half wave, the thyristors are fired only once the zero point has been passed. They are fired at the so-called "control angle α." The control angle is the angle between passing zero and the firing of the respective thyristor. It can have a maximum angle of 180° el., which corresponds to the end of the respective half wave – and subsequently the output power corresponds to 0. The minimum possible control angle is 0° el.; with this angle, firing occurs directly when passing zero. The mains voltage is subsequently switched through in full and the maximum possible power is output.

Figure 6 shows the situation for α = 45° el. A quarter of the time of the half waves passes before the mains voltage is switched through to the load.

Using thyristor power controllers in phase-angle operation is concomitant with 2 sometimes very disadvantageous effects: the occurrence of control reactive power and potential interference from harmonics. These issues are mostly avoided through the use of an electronic transformer, which is described in Chapter 1.3.

Figure 7 helps to illustrate the formation of control reactive power and harmonics for ohmic loads. It shows the data for a control angle of 90° el.

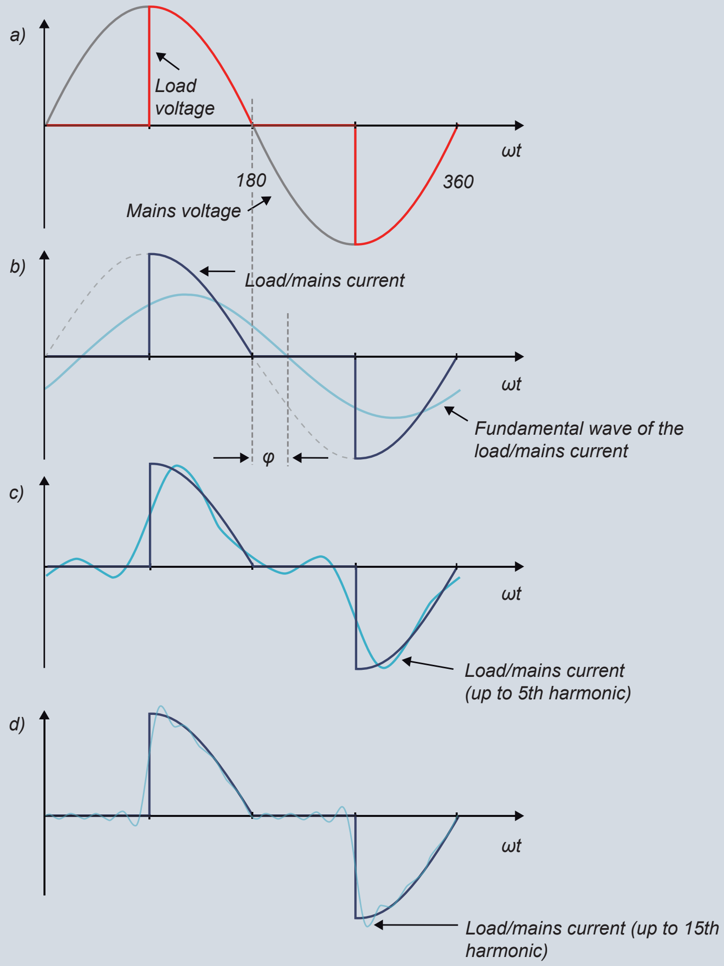


Figure 7: Electric variables in phase-angle operation for a control angle of 90° el.

Figure 7 shows the sinusoidal mains voltage and the load voltage produced through cutting the half waves (Figure 7a). In the case of resistive loads, the load/mains current (Figure 7b) has in principle the same curve as the load voltage. In fact the non-sinusoidal, periodic load/ mains current consists of a sine wave of the same frequency (50 Hz) and of multiples of this fundamental wave. The fundamental wave of the load current (Figure 7b) is shifted by the angle φ in relation to the mains voltage, which results in reactive power. The angle φ (and so the control reactive power proportion) increases as the control angle increases (this corresponds to a smaller percentage of power). That means that, for large control angles, a high amount of reactive power is produced in proportion to the amount of active power. From a correspondingly high ratio, the reactive power is charged by the energy supplier. In this case, it is generally better to reduce the reactive power by using compensation systems.

Figure 7c and Figure 7d illustrate the multiples of the mains current fundamental wave that form in the network. Figure 7c shows the sum of the fundamental wave and the multiples up to the 5th harmonic (250 Hz). The characteristic already gives an idea of the edges due to the phase angle control.

In Figure 7d, the additional multiples are included up to the 15th harmonic (750 Hz). Through the addition of harmonics with even higher frequencies, you would finally end up with the load/ mains current with its steep edges.

The current harmonics are fed back into the power supply network. Their amplitudes can also be calculated with the so-called Fourier analysis. They have a high potential to interfere and ultimately distort the mains voltage. Electrical consumers are disrupted and, from a certain proportion, the harmonics are no longer accepted by the energy supplier. In this case, filter systems must suppress the occurrence of harmonics.

The described issues in phase-angle operation (formation of control reactive power and harmonics) are all the most intensive the larger control angle α is (low percentage of requested power) and the larger the systems are. Interference suppression filters are generally used in phase-angle operation and sometimes compensation systems have to be installed.

A particular benefit is that the power controllers can switch between operating modes, meaning that the problem-riddled phase-angle operating mode is only used during a limited time period. For example, phase-angle control is used when starting from a cold state if there is a very low cold resistance at this operating point and current limiting is necessary. After the "soft start time" has elapsed, the power controllers switch to the problem-free burst-firing operating mode; it is assumed that the elements are heated and the element resistance is sufficiently high. The operating mode might also be switched due to a control signal.

As already mentioned, the nominal voltage of the heating elements generally corresponds to the mains voltage. When it comes to the ceramic heating elements for extremely high application temperatures, such as molybdenum disilicide ($MoSi_2$) and silicon carbide (SiC) heating elements, the nominal voltage is considerably lower than the mains voltage. If they are operated using a thyristor power controller, a transformer must be used.

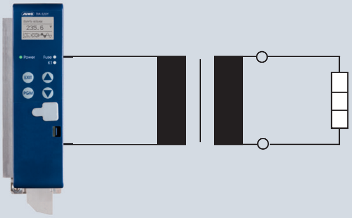


Figure 8: Basic principle of a thyristor power controller, transformer, and heating element

The power controllers usually work in phase-angle operation. However, the ratio of the transformer is dimensioned in such a way that normal operation is carried out with a correspondingly small control angle (small harmonic percentage, low reactive power).

Technically, it is possible to operate low-voltage heating elements without a transformer. For example, the load voltage can be adjusted to a third of the mains voltage by using phase-angle operation. The following table is based on a test measurement and shows the extremely high percentage of reactive power for large control angles:

Control angle [°]	Reactive/active power
170	86.0
160	13.6
150	7.0
140	4.0
130	2.8
120	2.1
110	1.6
100	1.3
90	1.0
80	0.8
70	0.6
60	0.5
50	0.4
40	0.3
30	0.2
20	0.1
10	0.0
3	0.0

Table: 1: Percentage of reactive power, relative to active power depending on the control angle

Table 1 demonstrates that already from control angles of 90° el., the reactive power is as large as the active power. For the largest control angle in the table (170° el.), the reactive power is 86x the value of the active power. If the nominal voltage of the elements deviates substantially from the mains voltage, the thyristor power controller must operate the heating elements by means of a transformer. The JUMO IPC 300 electronic transformer is the ideal device in this case, as it was developed specifically for this application.

1.3 JUMO IPC 300 electronic transformer

The JUMO IPC 300 operates heating elements whose nominal voltage is significantly lower than the mains voltage.

Figure 9: JUMO IPC 300 electronic transformer with choke (inductance) and heating element

The figure shows a schematic of the electronic transformer, the choke (part of scope of delivery), and the heating element. The transformer also comes with an EMC filter, which is designed for the maximum mains current that occurs in the application.

The JUMO IPC 300 is supplied with a voltage of AC 230 V or AC 400 V, for example, and varies the load voltage based on the temperature controller signal. The maximum value of the load voltage is adjustable; it is always below the voltage supply (buck converter).

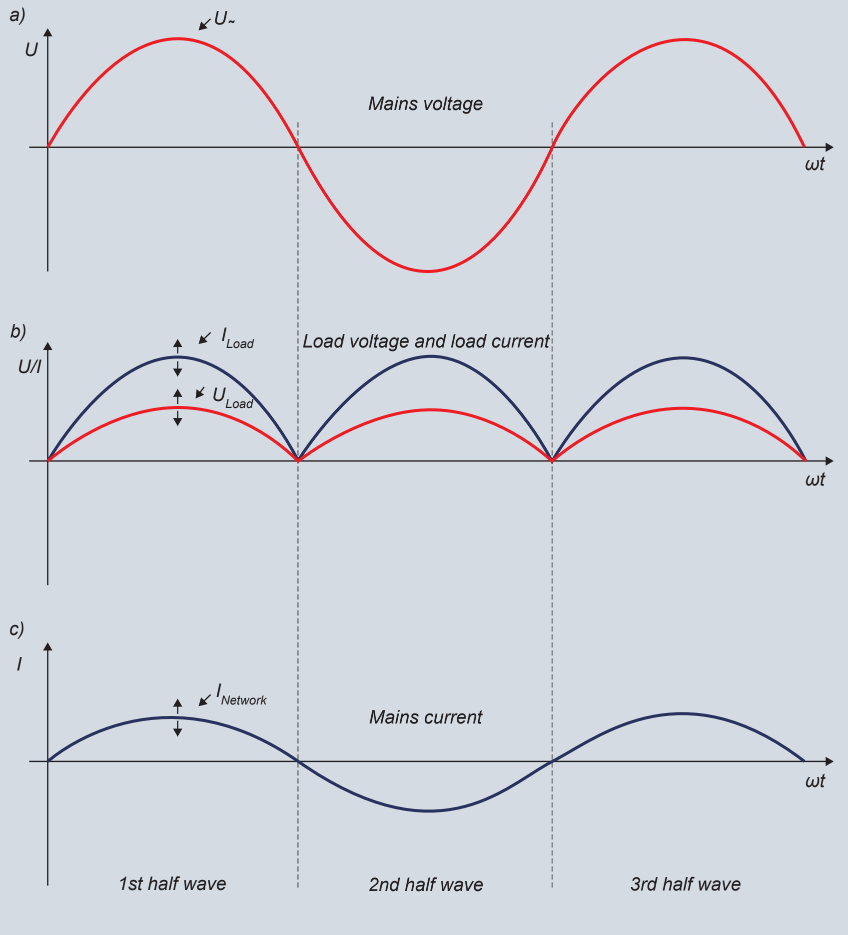


Figure 10: Mains voltage/current and load voltage/current for an electronic transformer

The load voltage also shows a sinusoidal curve (Figure 10b), but only the positive half waves are present. Due to the ohmic loads, the load current has the same shape of curve. The mains current (Figure 10c) has the same phase as the mains voltage. In this way, no significant reactive power is produced.

Figure 11 illustrates the function of the JUMO IPC 300:

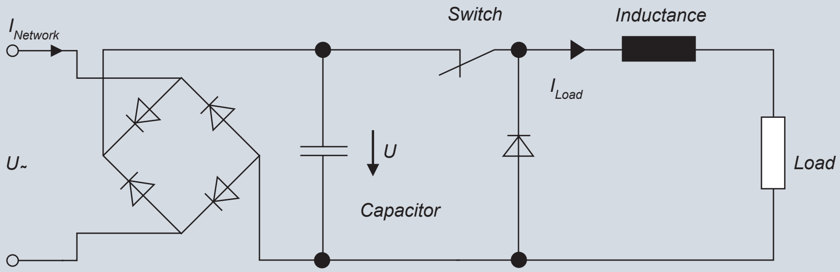
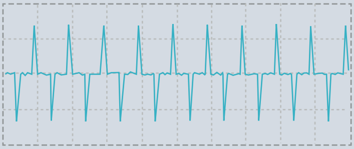


Figure 11: Circuit principle of the JUMO IPC 300 electronic transformer

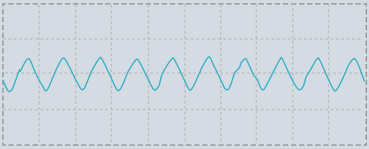
From the connected mains voltage, a pulsating direct voltage is produced in the DC link through the Graetz electrical circuit (Figure 11). The type of switch used is an IGBT switch, which runs at 16 kHz. There is also a pulsating direct voltage at the load. However, the IGBT switch-on/switch-off ratio and the inductance with flyback diode causes the amplitude of this voltage to vary: during the switch-on time, the load current increases in a delayed manner through the inductance – and thus so does the load voltage. If the IGBT is open,the decreasing current continues to flow (driven by the inductance) via the freewheeling diode.

Compared to operation with a thyristor power controller and a conventional transformer, a significantly lower proportion of harmonics is produced when using the electronic transformer. Figure 12 illustrates the result of a comparison measurement:

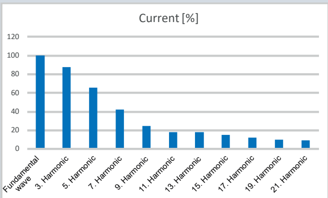
Mains current



Mains current



	Current [%]	Current [%]
Fundamental wave	100.0	100.0
3rd harmonic	87.5	7.9
5th harmonic	65.9	4.0
7th harmonic	42.0	1.3
9th harmonic	24.5	2.0
11th harmonic	18.0	2.2
13th harmonic	18.0	1.7
15th harmonic	15.4	2.6
17th harmonic	11.9	0.9
19th harmonic	10.0	1.5
21st harmonic	9.0	2.3



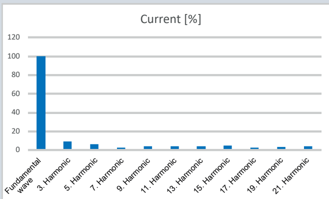


Figure 12: Mains current and harmonics spectrum of the JUMO TYA 201 thyristor power controller and JUMO IPC 300 electronic transformer in comparison

Figure 12 shows the steep edges of the mains current during operation with the thyristor power controller. On the other side is the almost sinusoidal mains current during operation with the electronic transformer. The proportion of harmonics – and thus the interference potential – is significantly lower with the electronic transformer. As an example for comparison: with the thyristor power controller, the 3rd harmonic of the mains current is 87.5 % of the fundamental wave, but with the electronic transformer, it is only 7.9 %.

2 Subordinate control loops

The clue to the basic function of the "power controller" is in its name: it controls the power based on a control signal:

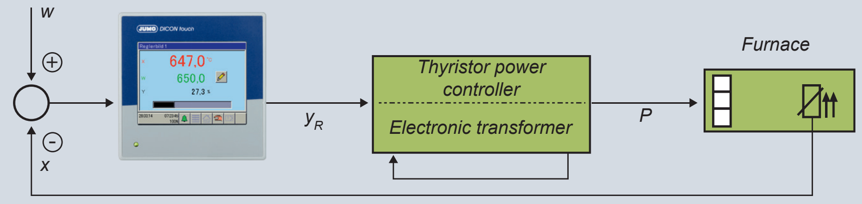


Figure 13: Subordinate control loop of the actuators

The actuators receive the setpoint value from the output level of the temperature controller (y_R) and control the power (P) at their output in proportion to this signal. The backwards-pointing arrow represents the subordinate control loop in Figure 13. For example, at an output level of 0 to 100 %, a temperature controller outputs a current signal of 4 to 20 mA, and the actuator adjusts the power to between 0 and 20 kW in proportion to this signal.

It is not always the power at the load that is adjusted. It is more cost-effective to control the square of the load voltage in proportion to the control signal. With the subordinate U^2 control loop, the power at the heating element also increases linearly to the control signal if the element resistance stays the same.

Here is an example:

The nominal voltage of a heating element is AC 230 V and the nominal power is 10 kW. The formula for electrical power ($P = U^2/R$) can be used to calculate the element resistance of 5.29 Ω.

U^2 is selected as the subordinate control loop on the actuator and the maximum voltage to be output is configured (AC 230 V). The actuator adjusts the square of the load voltage at the load output in proportion to the control signal. If y_R = 100 %, the output voltage is AC 230 V. If you square this value, you get 52,900 V^2. If y_R = 50 %, the actuator adjusts the output voltage to half of $(230\ V)^2$, which equates to 26,450 V^2 or $(162.6\ V)^2$.

Required output level (%)	Square of the load voltage (V^2(AC))	Load voltage (V AC)	Power at the load (KW)
0	0	0.0	0
10	5,290	72.7	1
20	10,580	102.9	2
30	15,870	126.0	3
40	21,160	145.5	4
50	26,450	162.6	5
60	31,740	178.2	6
70	37,030	192.4	7
80	42,320	205.7	8
90	47,610	218.2	9
100	52,900	230.0	10

Table 2: Power as a linear function of the control signal when using U^2 control (example)

The square of the load voltage is increased in proportion to the output level.

The values for the power at the load can be traced back (Table 2) by dividing the square of the load voltage by the example element resistance (5.29 Ω).

Furthermore, the subordinate **U^2 control** provides operational safety if 1 or several of the elements connected in parallel break(s):

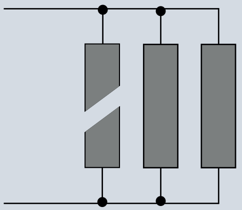


Figure 14: Break in 1 of 3 elements connected in parallel

With U^2 control, the power at the remaining elements is not increased after an element breaks, as the load voltage continues to remain constant. With subordinate P control loop on the other hand, there is an attempt to adjust the requested power with the remaining elements: the load voltage is increased, which increases the load on the elements and could even destroy them.

The actuators can continue to adjust the square of the load current in proportion to the control signal. Even with the **rarely used I^2 control**, the power at the load increases in proportion to the control signal if the load resistance remains constant ($P = I^2 \times R$).

Here is an application example: you have a resistance wire and every meter of wire is meant to convert a certain amount of electrical power into thermal energy. The length of the wire can vary depending on the application or type of system. This can be achieved using a defined load current ($P = I^2 \times R$). The current must also remain constant with a longer wire (and thus with a higher load resistance). Once the subordinate I^2 control loop has been selected, the current is adjusted to a defined value. If the wire is longer, the current is kept constant by increasing the voltage, and the power per meter remains constant.

I^2 control is also used if the amperage has to be in proportion to the control signal (such as in electroplating operations for example). Instead of I^2 control, I control can also be selected in the actuators; the load current is subsequently adjusted linearly to the control signal (not squared).

If **P control** is selected, the actuators vary the power at the load based on the control signal. P control is also not used very often. A classic example of when it is used is in the operation of **silicon carbide (SiC) heating elements**. The surface temperatures of these ceramic elements can go up to approx. 1600 °C. Figure 15 shows the particular resistance behavior of these elements depending on temperature:

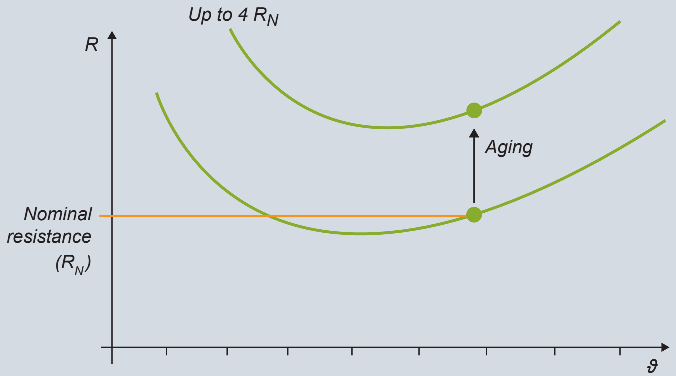


Figure 15: Temperature behavior of a SiC heating element

When in a cold state, the elements have a high resistance. As the temperature increases, the resistance falls, until it eventually starts increasing again. The strong influence of temperature on the resistance is a reason not to use U^2 control: with a constant control signal/constant load voltage, the power ($P = U^2/R$) would automatically increase as the temperature of the elements increases, until it eventually decreases again.

Figure 15 also illustrates another property of the SiC elements: as they age, they increase their resistance value by up to a factor of four. This is another reason for not using U^2 control: if U (or U^2) remains the same, the elements would output just a quarter of their original power ($P = U^2/R$) by the end of their service time.

When using SiC heating elements, the subordinate P control loop is used. Due to the aging-related increase in resistance of the elements, and the resulting need to increase the load voltage, a transformer needs to be used. We would recommend using the JUMO IPC 300 electronic transformer, or you could also use the JUMO TYA thyristor power controller with a traditional transformer (see Chapter 5.2).

3 Versions, dimensioning, and connecting the actuators

The JUMO IPC 300 electronic transformer is used whenever the nominal voltage of the heating elements is lower than the voltage supply. Using a thyristor power controller in phase-angle operation is only acceptable for relatively low deviations.

The heating elements operated with thyristor power controllers have a nominal voltage that is at the level of the voltage supply. This corresponds to the **phase voltage U_N** (voltage between the phase and N-conductor) or the phase-to-phase voltage (voltage between 2 phases). The **phase-to-phase voltage U_L** is calculated by **multiplying the phase voltage by the factor √3**.

Normally, the heating elements are operated in AC 3/N/400/230 V low-voltage networks. Accordingly, the phase voltage is AC 230 V and the phase-to-phase voltage is AC 400 V. The nominal voltage of the heating elements is at the level of 1 of these values or it is determined as a result of interconnecting the heating elements.

In all actuators, there is an exchangeable semiconductor fuse for protecting the thyristors or the IGBT.

As a result of the switching current, there is power loss in both systems (P_{loss}), and thus waste heat is produced. The energy has to be conducted away from the mounting site (normally a control cabinet). With thyristor power controllers, the power loss is calculated using a rule of thumb:

P_{loss} = number of switched phases x (20 W + 1.3 V × I_{Load})

The number of switched phases for the JUMO TYA 201 is 1, for the JUMO TYA 202 it is 2, and for the JUMO TYA 203 it is 3.

In the operating manual for the JUMO IPC 300, there are formulas for calculating the power loss. The resulting values are higher than those for the thyristor power controllers. The formulas calculate the losses in the JUMO IPC 300 and in the network filter. If these are to be compared with applications for a thyristor power controller, the losses in the transformer and in the filter have to be added to the power controller losses (see above formula).

For the actuators, the setpoint value can be specified via a current or voltage signal. Different inputs are provided for this purpose. The actuators can also be actuated via a bus system, such as PROFINET, or a serial interface (Modbus).

3.1 Versions, dimensioning, and connection of the JUMO TYA 200 thyristor power controller

The thyristor power controllers are available in different versions: 1 version for 1-phase operation, and 2 other versions for 3-phase operation.

The 1-phase power controller (JUMO TYA 201) can operate heating elements between the phase and the N-conductor, or between 2 phases. With the JUMO TYA 202, 3-phase loads are connected in a three-phase economy circuit, which is cost-effective. Only burst-firing operation is possible with this power controller. For 3-phase loads with the JUMO TYA 203, burst-firing operation and phase-angle operation are carried out in a 4-wire circuit. If a bit more wiring effort is accepted and the so-called 6-wire circuit is used, a lower actuator current is produced in the JUMO TYA 203 with the same power.

This chapter contains information on dimensioning power controllers. Table 3 provides an initial overview:

	JUMO TYA 201	**JUMO TYA 201**	**JUMO TYA 202/ JUMO TYA 203**	**JUMO TYA 203**
Operating mode	Phase/N-conductor	Phase/phase	Three-phase economy circuit/ 4-wire circuit	6-wire circuit
Voltage supply, control electronics	Phase voltage (U_N)	Phase-to-phase voltage (U_L)	Phase-to-phase voltage (U_L)	Phase-to-phase voltage (U_L)
Calculation of the actuator current	P/U_N	P/U_L	$P/(3 \times U_N)$	$P/(3 \times U_L)$

Table 3: Voltage supply to control electronics, and power controller current in the various applications

The formula for the power controller current applies for a symmetrical load distribution with the 3-phase actuators (JUMO TYA 202/203). Power P to be used corresponds to the total power of all connected heating elements.

3.1.1 The power controller for 1-phase operation: JUMO TYA 201

The JUMO TYA 201 thyristor power controller is used for 1-phase operation (Figure 16).

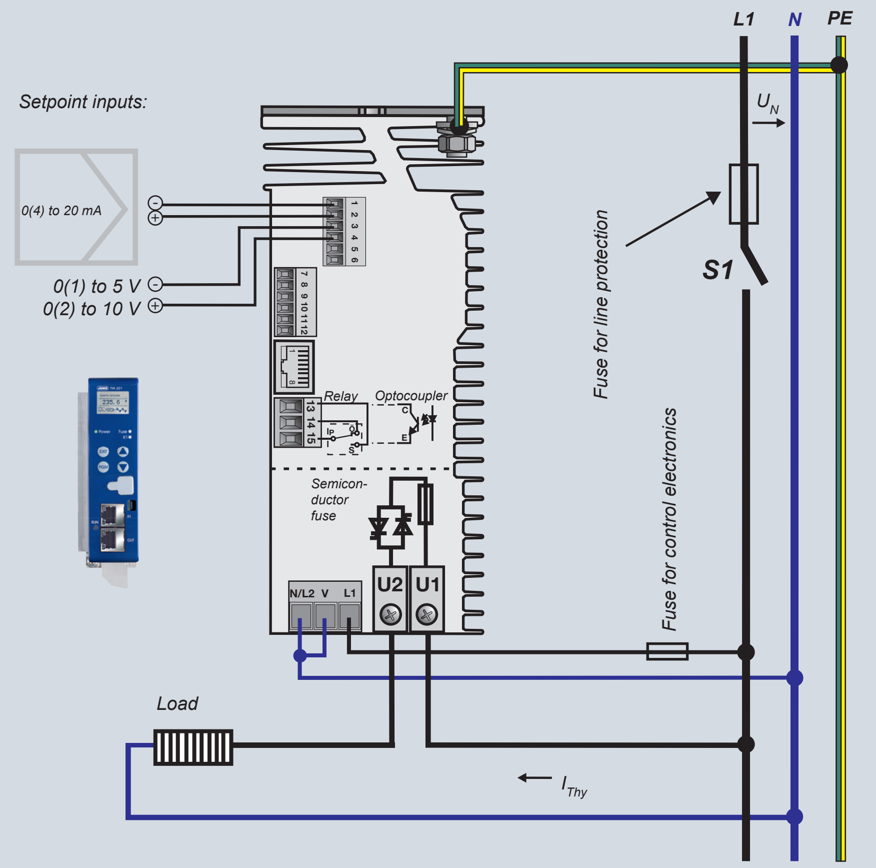


Figure 16: Connection of a JUMO TYA 201 when operating a load between the phase and N-conductor

Figure 16 shows the application of the 1-phase power controller for operation between the phase and N-conductor. The phase is connected via the thyristors (U1-U2) to the load; the other side of the heating element is connected with the N-conductor. To supply the control electronics with power, the phase voltage is also connected (L1-N/L2). The power controllers can be ordered for supplying different levels of voltage to the control electronics (AC 115 V, 230 V, 400 V, and others). The voltage selected for the control electronics must be at the level of the phase voltage (AC 230 V in the AC 3/N/400/230 V networks). For the supply of the load and the control electronics the same voltage is connected.

In many cases, the power controller receives its setpoint value from the temperature controller via a current signal (terminal 1 and 2 in Figure 17). If voltage signals are used, the other inputs are used.

The power controllers can be ordered for different maximum currents that can flow via the thyristors (AC 20 A, 32 A, 50 A, 100 A, 150 A, 250 A). The current that flows in the application is not allowed to exceed the respective maximum current.

For example: a heating element has a nominal voltage of AC 230 V and a nominal power of 7 kW. The heating element is operated between the phase and N-conductor. The power controller selected must be for a voltage supply of AC 230 V. The maximum current that can flow is AC 30.4 A (7000 W/230 V). For that reason, the power controller selected must be for a maximum current of 32 A.

If the heating element has a nominal voltage that is at the level of the phase-to-phase voltage, it is operated between 2 phases:

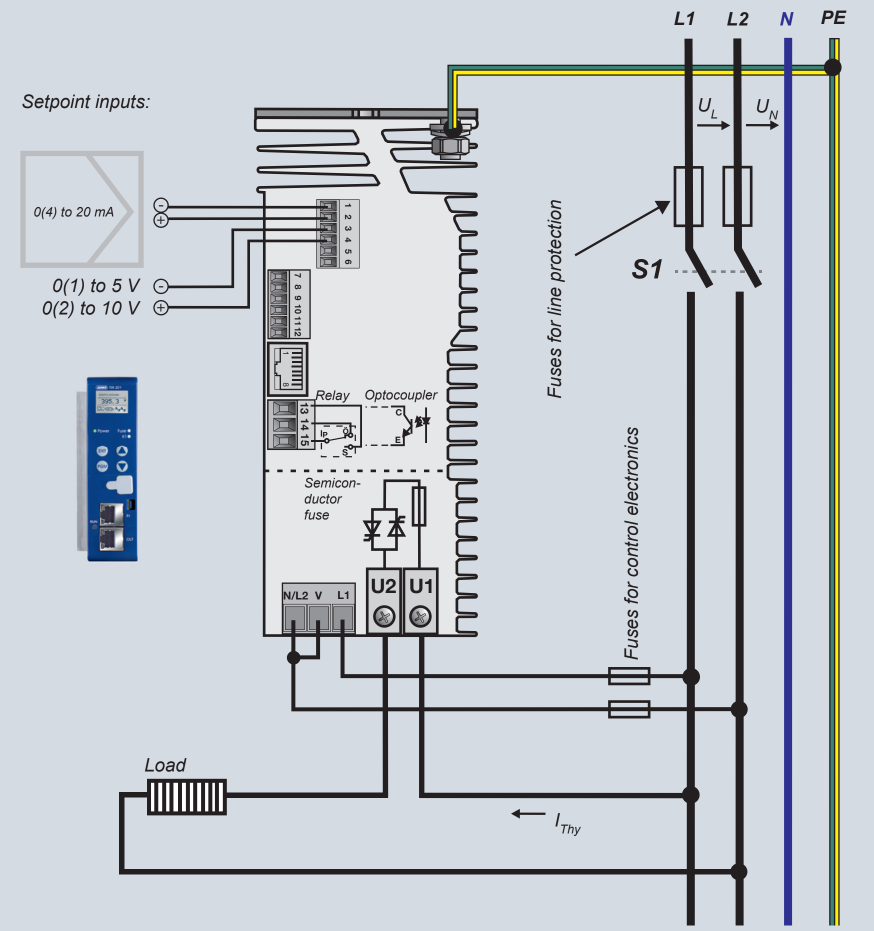


Figure 17: Connection of a JUMO TYA 201 when operating the load between 2 phases

The load is supplied with the phase-to-phase voltage via the thyristors (Figure 17). The same voltage is used to supply the control electronics – a power controller for the phase-to-phase voltage must be selected (AC 400 V for AC 3/N/400/230 V).

For example: a heating element has a nominal voltage of AC 400 V and a nominal power of 15 kW. The heating element is operated between 2 phases. The power controller selected must be for a voltage supply of AC 400 V. The maximum current that can flow is AC 37.5 A (15,000 W/400 V). For that reason, the power controller selected must be for a maximum current of 50 A.

3.1.2 The thyristor power controllers for 3-phase operation: JUMO TYA 202 and JUMO TYA 203

There are 2 options when it comes to 3-phase operation: if there is no need for phase-angle operation, the JUMO TYA 202 is the power controller to use. Otherwise you use the JUMO TYA 203. The loads can be connected in star or delta connection. Apart from the 6-wire circuit outlined at the end of the chapter, the thyristor current in symmetrical load distribution is calculated based on the total power divided by 3x the value of the phase voltage (see formula in Table 3).

The power controllers consist of a master and 1 or 2 slaves (see Figure 18 and 19). The master device controls operation. It is located on the left-hand side and has a display and keypad. Depending on whether 2 or 3 phases are switched, there are 1 or 2 slaves to the right of the master. The slaves are connected to the master via a patch cable. Configuration is carried out on the master device only – either using the keypad or the configuration program.

Both power controllers for 3-phase operation can also operate the loads via transformers. This becomes necessary if the nominal voltage of the 3-phase heating element is significantly lower than the phase-to-phase voltage of the low-voltage network. In these cases, however, it is advisable to use the JUMO IPC 300 electronic transformer.

When connecting the power controllers and loads, make sure the rotating electrical field runs clockwise.

The **JUMO TYA 202** (Figure 18) enables 3-phase loads to be operated cost-effectively:

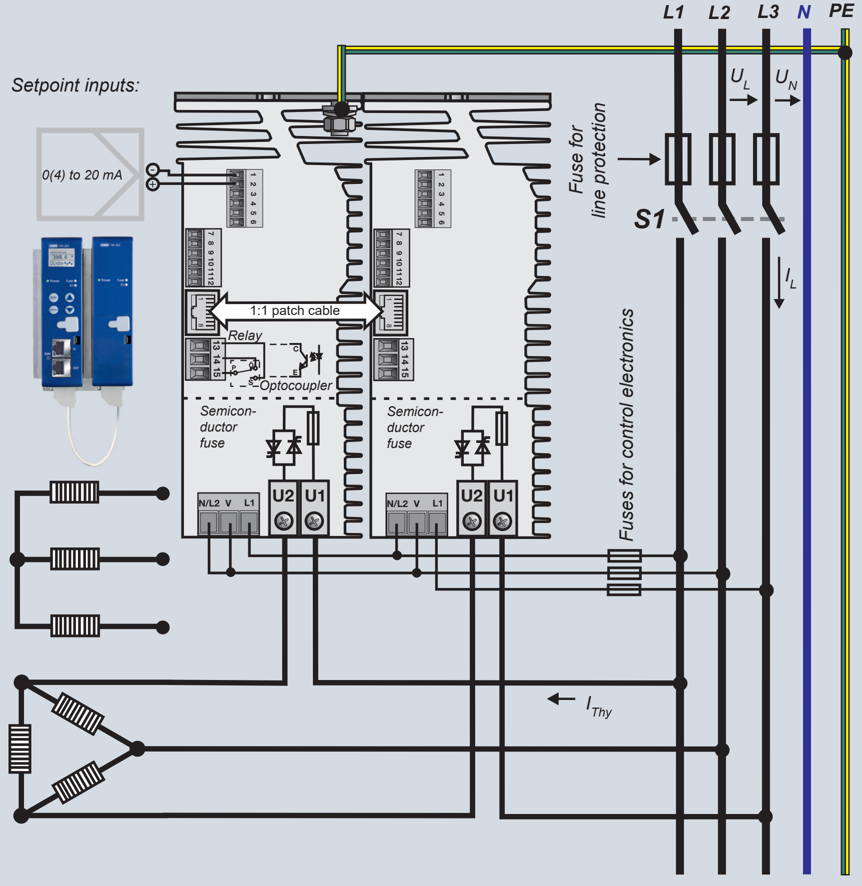


Figure 18: Operation of 3-phase loads in a three-phase economy circuit with the JUMO TYA 202

With this power controller, only 2 phases (L1 and L3) are connected via the thyristors; the 3rd phase (L2) is connected directly to the load. Phase-angle operation is not possible in this "three-phase economy circuit," and in star connection the start point cannot be connected with the N-conductor. This means that the power controller cannot be used if current limiting is required or if the nominal voltage of the load is lower than the phase-to-phase voltage (delta connection) or lower than the phase voltage (star connection).

For example: a power controller is dimensioned for a load switched in delta connection. The nominal voltage of the load is AC 400 V and the total power is 30 kW. It is connected to the AC 3/N/400/230 V low-voltage network. The **voltage supply for the control electronics** must be selected at the level of the phase-to-phase voltage at **AC 400 V**. To calculate the power controller current – regardless of whether the load is in star or delta connection – use the formula from Table 3: 30,000 W/(3 × 230 V) = 43.5 A. From among the various power controller variants, with respect to the power controller current (AC 20, 32, 50, 100, 150, 250 A), the power controller that is selected must be able to switch the calculated current at minimum: **50 A**.

If phase-angle operation is necessary, the JUMO TYA 203 is used:

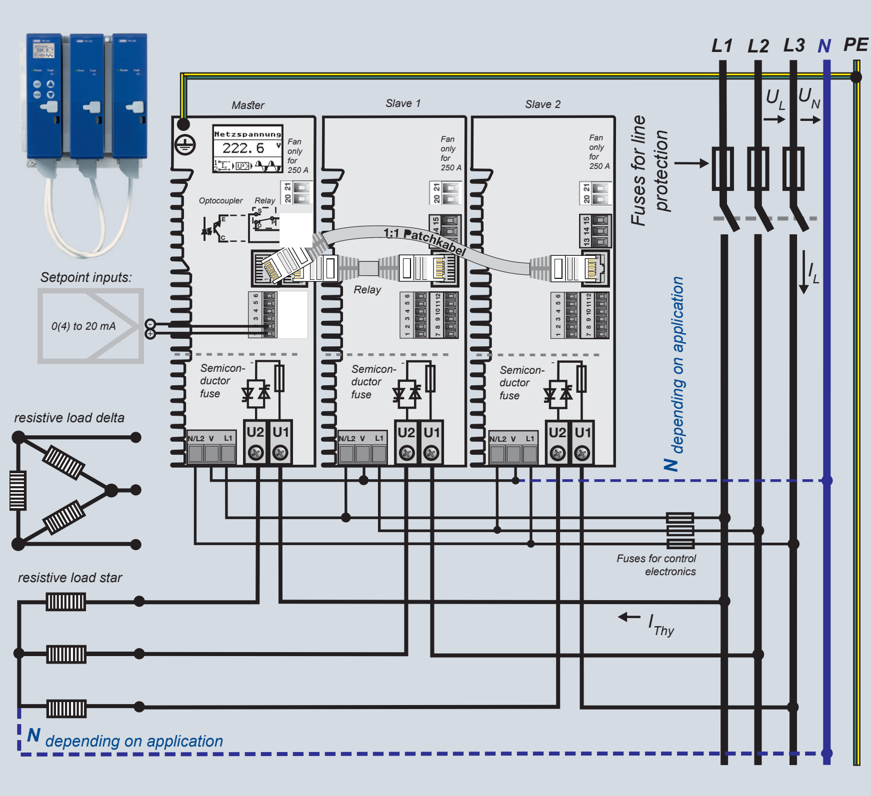


Figure 19: Operation of 3-phase loads in a 4-wire circuit with the JUMO TYA 203

The 3-phase load is usually connected in a 4-wire circuit (three phase conductors and an N-conductor). The load can be connected as a delta or star connection. Depending on the application, the star point can also be connected to the N conductor if required. When connecting the star point in phase-angle operation, it is important to take into account that the current in the neutral conductor might sometimes be significantly higher than the current in a phase conductor. This can be explained by the fact that the cut current half waves consist of a fundamental wave of equal frequency and harmonics with a multiple of this frequency.

If the nominal voltage of the partial loads is at the level of the phase-to-phase voltage (AC 400 V for AC 3/N/400/230 V), these can also be connected to the JUMO TYA 203 in a 6-wire circuit (or in an open delta circuit) (Figure 20).

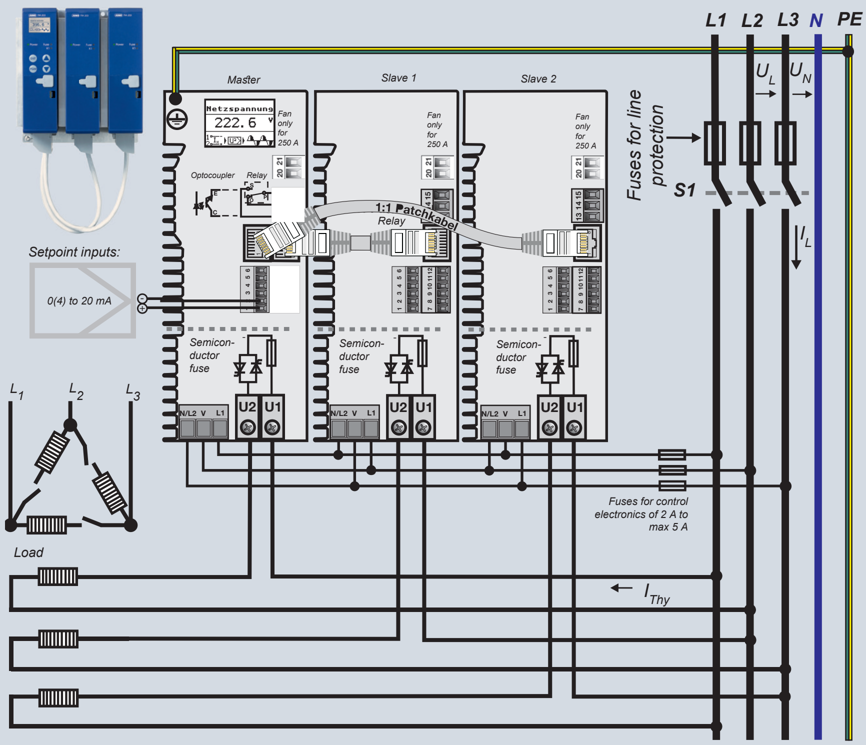


Figure 20: Operation of 3-phase loads in a 6-wire circuit with the JUMO TYA 203

In this electrical circuit, the loads can only be connected as a delta connection. If you accept the fact that there will be slightly more wiring involved, then you'll be rewarded with a power controller current for your application that is smaller by the factor $\sqrt{3}$, and thus a smaller power controller may be sufficient.

For example: the JUMO TYA 203 is dimensioned in a 6-wire circuit for operation of a 3-phase load (nominal voltage AC 400 V and total power 30 kW). This corresponds to the same load for which, previously, the JUMO TYA 202 was dimensioned. It is connected to the AC 3/N/400/230 V low-voltage network. The voltage supply for the control electronics must be selected as AC 400 V – at the level of the phase-to-phase voltage. To calculate the power controller current, take the power and divide it by 3x the value of the phase-to-phase voltage (instead of the phase voltage): 30,000 W / (3 × 400 V AC) = 25 A (instead of 43.5 A). From among the various power controller variants with respect to the power controller current (AC 20, 32, 50, 100, 150, 250 A), the one that is selected must correspond to the expected current at minimum: 32 A (instead of 50 A).

3.2 Versions, dimensioning, and connection of the JUMO IPC 300 electronic transformer

Compared to the thyristor power controllers, the JUMO IPC 300 comes in a more manageable number of variants. The electronic transformer has been designed for 1-phase operation (Figure 21) and the control electronics are generally supplied with DC 24 V (L+ and L-).

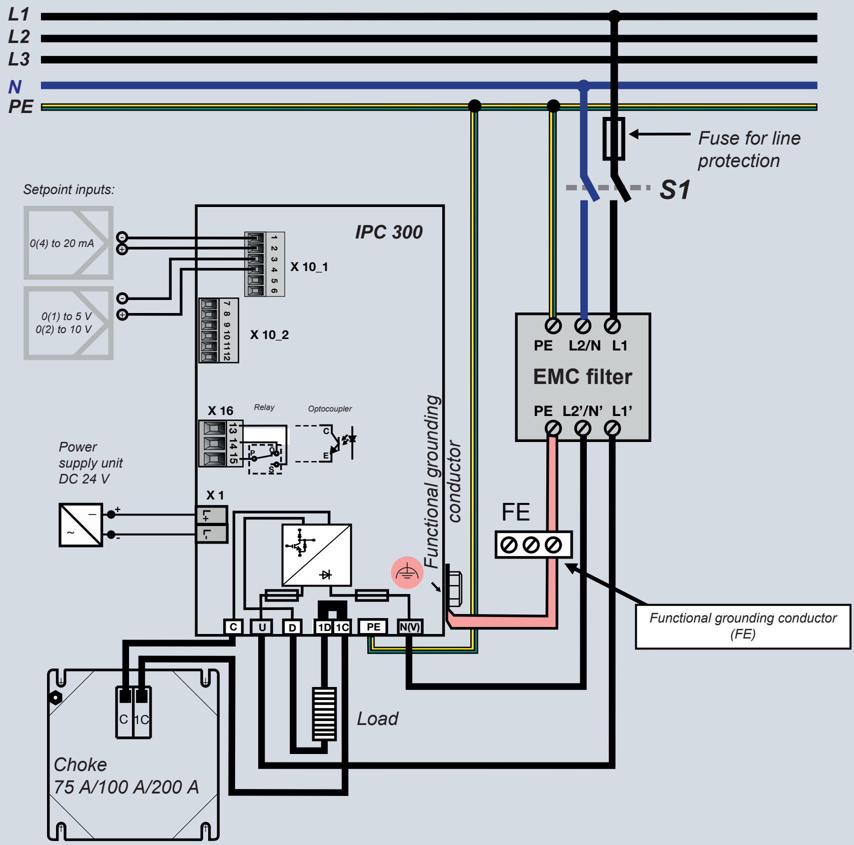


Figure 21: Connection of the JUMO IPC 300 to phase and N-conductor via the EMC filter

The power section of all versions can be supplied with a voltage in the range of AC 20 to 400 V. The JUMO IPC 300 is also normally operated in the AC 3/N/400/230 V low-voltage networks, where the power section is either supplied with AC 230 V (phase voltage, see Figure 21) or with AC 400 V (phase-to-phase voltage). The maximum load voltage can be adjusted. It is adjusted to the nominal voltage of the elements. For the named voltage supplies, the maximum load voltage can be adjusted to values of up to AC 210 V or AC 380 V.

The output of the JUMO IPC 300 is fed via the choke (C and 1C) and connected to the load (1D and D). For example, a temperature controller specifies the setpoint value with a signal of 4 to 20 mA, and the JUMO IPC 300 increases the load voltage at the output depending on this signal.

There are 3 different versions of the JUMO IPC 300, which differ by their maximum load current (70 A, 100 A, and 200 A).

The choke is connected to the load in series. Depending on the load current in the application, select the smallest possible choke (75 A, 100 A, and 200 A) that is compatible with the occurring load current at minimum.

The EMC filter that is to be selected depends on the mains current that occurs. For the JUMO IPC 300, the mains current does not correspond to the load current. To calculate the approximate mains current, use the following formula:

$$I_{Network} = \frac{\text{maximum load power consumption}}{\text{voltage supply for power section}}$$

There is actually a higher mains current due to the additional power loss. However, significant changes for the calculation of the mains current result only for the operation of smaller loads (see operating manual).

The filter used must be the smallest one possible, but must, at minimum, be compatible with the mains current of the application (16 A, 20 A, 32 A, 63 A, and 100 A). The largest filter available determines the maximum mains current for all applications: 100 A.

For example: you want to determine the maximum possible power at the load for the largest JUMO IPC with 200 A load current, and the power section is supplied with AC 400 V: a maximum power of 40 kW can be taken from the network (AC 100 A × 400 V). Minus the losses, 38 kW is supplied to the load (see operating manual for the JUMO IPC 300). Or from the opposite viewpoint: the JUMO IPC 300 for 200 A load current can output this current with voltages of up to AC 190 V (AC 190 V × AC 200 A = 38 kW).

4 Configuration, operation, and functionalities of the actuators

4.1 Configuration of the actuators

The actuators are configured using the keypad and display, or using the configuration program. There is a diverse range of configuration options. However, the parameterization of the basic function is very simple.

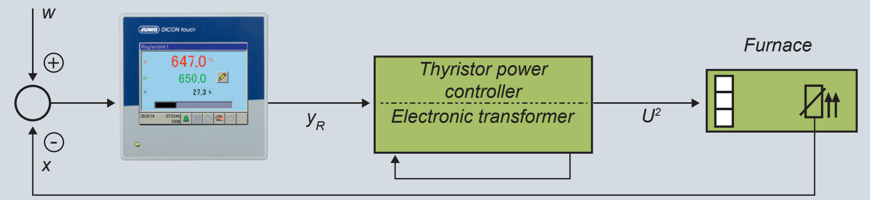


Figure 22: The actuators in the control loop

First, the signal for the setpoint specification is defined, which is carried out via the current input with the default settings (Figure 23). Alternatively, the settings can be applied so that the setpoint value is defined via the voltage input or via the interface.

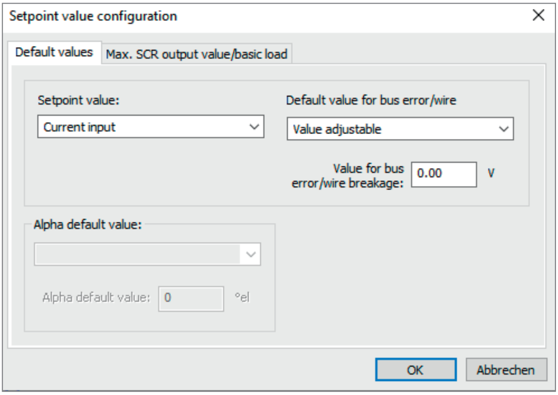


Figure 23: Selection of the source for the setpoint specification when using the JUMO TYA 200 (configuration program)

With the default settings, the square of the load voltage is adjusted in proportion to the setpoint signal. The maximum load voltage (for the maximum control signal) must be set (Figure 24).

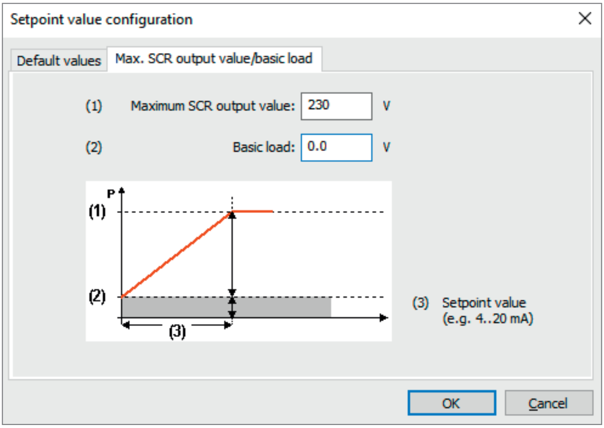


Figure 24: Setting of the maximum load voltage for the JUMO TYA 200 (configuration program)

If 1 of the other 2 subordinate controls is set, the maximum load current (for I^2 control) or the maximum power at the load (P control) is defined in the submenu.

For the JUMO IPC 300 electronic transformer, all 3 maximum values are generally specified (load voltage, load current, power for the load). 1 variable is changed depending on the control signal (default setting: the square of the load voltage). However, the respective variable is only increased for as long as neither of the other 2 variables is above its defined maximum value.

When it comes to the thyristor power controllers, the user must also define whether these are to function in burst-firing operation or phase-angle operation:

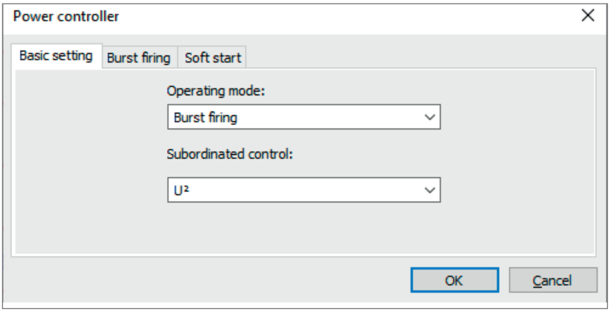


Figure 25: Selection of the subordinate control when using the JUMO TYA 200 (configuration program)

4.2 Operation of the actuators

Once the steps described in Chapter 4.1 have been completed, the actuators are ready for operation. In the measurement overview, they display the source for the setpoint specification (current input, voltage input, or interface), the chosen subordinate control loop, and important electrical parameters (Figure 26). This means that no measurement instruments are required for startup.

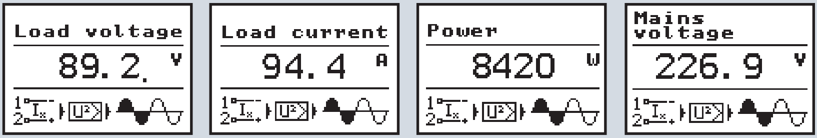


Figure 26: Measurement overview for a JUMO TYA 201 thyristor power controller

The thyristor power controllers also show the operating mode (burst-firing or phase-angle operation).

To check the load circuit, a setpoint can be specified for the actuators in manual mode, without a temperature controller control signal being required.

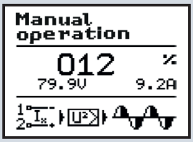


Figure 27: Display on the JUMO TYA 201 after activating manual mode and specifying the setpoint as 12 %

4.3 Actuator functionalities

The actuators have various different additional functions, a selection of which are described in this chapter.

4.3.1 Current limiting

Current limiting is mainly used when heating elements have an extremely low cold resistance (Figure 28).

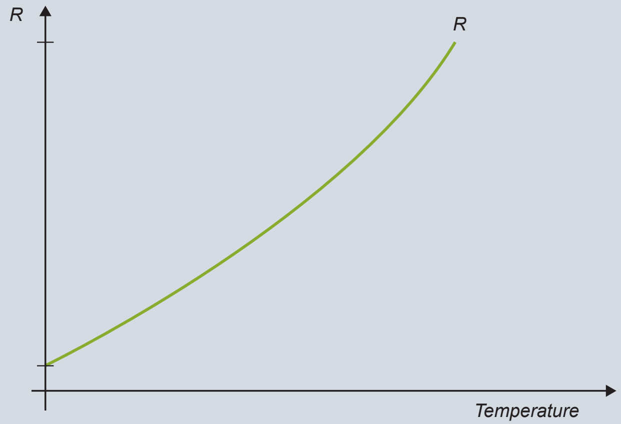


Figure 28: Heating element with positive temperature coefficient and very low cold resistance

If systems are started up from a cold state, it is highly likely that a temperature controller will specify the output level as 100 %, due to the high setpoint and the low actual value. The output level of the temperature controller is the setpoint for the actuator, which means that, for example, the load voltage is adjusted to the value set for "Maximum SCR output value" (Figure 24). If the heating element has a very low cold resistance (Figure 28), the high load voltage will result in a relatively high load current, which will destroy the exchangeable semiconductor fuse in the actuator.

Current limiting limits the load current to a set value, which, for example, can be the nominal current of the actuator. The current is generally only limited for a relatively short period of time when starting up from a cold state. After this, the current value falls below the set limit value again due to the relatively high resistance of the elements.

To be able to use the current limiting function, a thyristor power controller must be used in phase-angle operation. If a high setpoint value is specified for the power controller, the power controller – starting with 180° el. – reduces the phase angle: the load voltage and load current increase. Once the limit value for the current has been reached, there is no further reduction of the control angle, and the current stagnates.

The disadvantages of using phase-angle operation are that it produces control reactive power and harmonics. However, as this operating mode is generally only required when starting up from a cold state, the following approach can be a good solution: 1 contact at 1 of the power controller's binary inputs can be used to control the operating mode. If the contact is open, phase-angle operation is used and the current is limited to the set value. When the contact closes, the power controller switches to burst-firing operation and the current is no longer limited.

With the IPC, maximum values are always set for the load current, load voltage, and power (Figure 29). The system regulates to 1 of the variables; the other 2 values are never exceeded, however. Figure 29 shows the settings for when the load voltage is to be adjusted to a maximum of 80 V when using U^2 control, but the load current is not allowed to exceed 60 A in all cases.

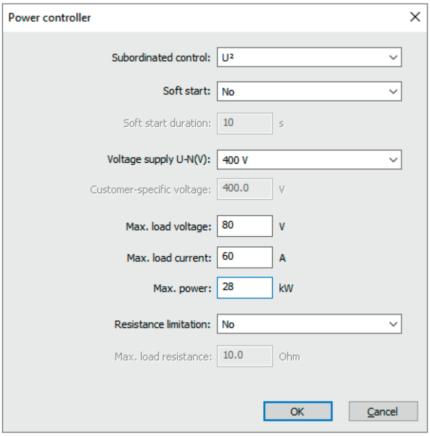


Figure 29: Current limiting settings for a JUMO IPC 300

The default value predefined for "Max. power" corresponds to the maximum possible output power of the JUMO IPC 300 in use. The default setting is 28 kW for a transformer used with a load current of 70 A. It has been left unchanged and this power is never reached in the application. This setting has no relevance for the application.

4.3.2 Soft start

The setpoint value for the actuators can increase in steps. This behavior causes the heating elements to heat up very quickly. More gentle heating is achieved by the soft start function. The setpoint value of the actuator is then ramped up over a certain time until the required final value is reached.

With the JUMO TYA 200, soft start can be activated for burst-firing operation for example, and a soft start time can be set. If, for example, the required power for a power controller increases abruptly from 0 to 50 %, the thyristor power controller keeps switching through more and more full waves until the soft start finishes and 50 % of the mains voltage full waves are applied at the load.

If the soft start function is used in phase-angle operation, the power controller starts with a control angle of 180° el. and reduces this to 90° el. during the soft start (at 50 % output level).

For heating elements with a very low cold resistance (such as in Figure 28), the power controller can, in principle, operate in burst-firing operation, but in this case the soft start must be carried out with phase-angle control (Figure 30).

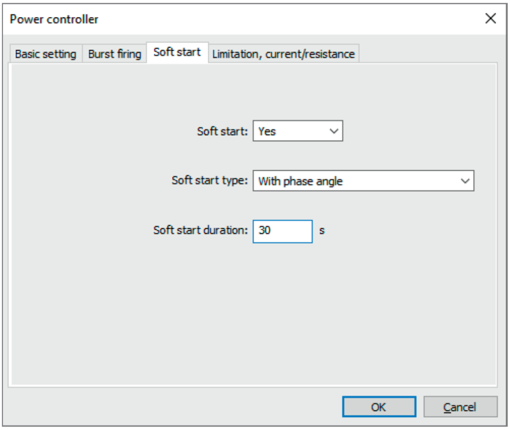


Figure 30: Settings for soft start with phase-angle control for a power controller in burst-firing operation (configuration program)

If there is a setpoint specification starting from 0, the soft start phase starts. Starting with a control angle of 180° el., each half wave is cut. The control angle is reduced until it reaches 0° el. once the soft start time has elapsed. After this, the power controller operates in burst-firing operation again.

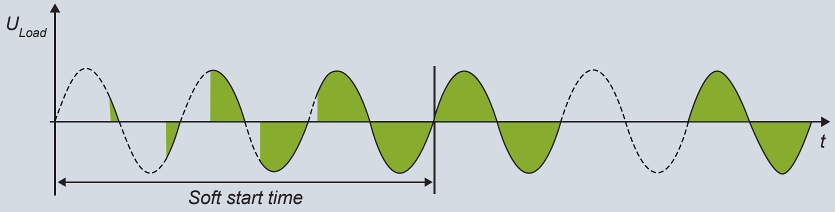


Figure 31: Soft start with phase-angle control for a power controller in burst-firing operation

After activating "soft start with phase-angle control," a current limit value can be set. If the load current reaches this value during the soft start, current limiting is active and the control angle is reduced no further. Despite the current limiting, the heating element is heated up and its resistance increases. The higher resistance causes the current to decrease and fall below the current limit value. Next, the control angle is reduced further until it eventually reaches 0 °el., and the soft start phase is finished.

With the JUMO IPC 300, the voltage amplitude is increased during the soft start phase until the required setpoint has been reached.

If the setpoint value for the actuators is 0 % for longer than 8 seconds, soft start is used again following another setpoint value increase.

4.3.3 Load monitoring

Several heating elements are often connected to the actuators in parallel or in series (Figure 32).

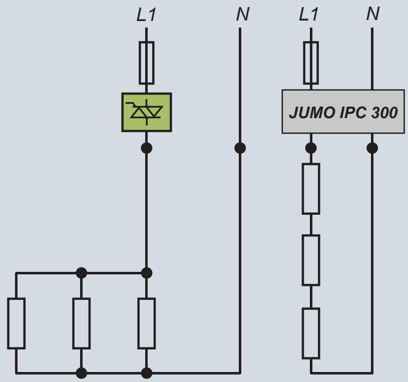


Figure 32: Connection of several heating elements to JUMO TYA 201 or JUMO IPC 300

A JUMO TYA 201 is used for the heating elements connected in parallel (left). It is often operated with a subordinate U^2 control loop. If the nominal voltage of the heating elements is at the level of the phase voltage, this is set as the maximum actuating variable on the power controller (230 V in the systems AC 3/N/400/230 V). Because the loads are connected in parallel, the power that is output is tripled compared to operation with just 1 heating element. If 1 of the elements breaks, the power reduces by a third; this load error can be monitored. Due to this error being signaled, the user knows to replace the broken element the next time the system is shut down.

The load monitoring detects the percentage change in resistance at the load. It can detect and signal a load failure, partial load failure, or a partial load short circuit. The function is particularly useful when using heating elements that hardly change their resistance due to temperature.

With elements connected in parallel, the load current decreases when an element breaks. That is why, in the actuator monitoring settings, the load monitoring is set to the undercurrent option (Figure 33):

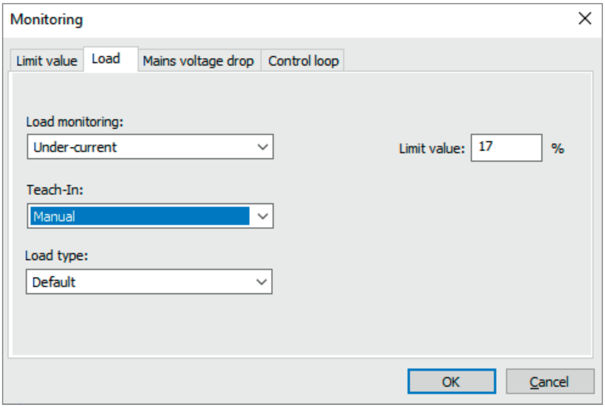


Figure 33: Load monitoring settings for 3 elements connected in parallel (configuration program)

Elements connected in series can be monitored for short circuit (Figure 32, to the right). In the event of this malfunction, the load current becomes larger, and "Over-current" is thus set under load monitoring (Figure 33).

The limit value for the load monitoring (Figure 33) is the percentage change in resistance of the load, at which the monitoring is activated. If the resistance of the heating elements does not change when the temperature changes, the limit value that needs to be set – which is based on the number of elements connected in parallel – can be found in the actuator documentation:

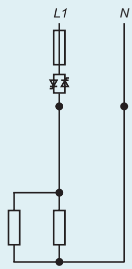
Number of heating elements	*Single-phase operation*
5	***10 %***
4	***13 %***
3	***17 %***
2	***25 %***
1	***50 %***
Example: 2 heating elements	

Table 4: Load monitoring limit values to be set for different numbers of elements connected in parallel using the JUMO TYA 201 (or the JUMO IPC 300)

The actuator must determine the resistance of the interconnected heating elements. If the actual resistance deviates by more than the configured limit value percentage, the monitoring is activated. The resistance is measured via the "Teach-In" function. If the "Manual" option is selected, like in Figure 33, a typical output level is set during startup in manual mode (for example 70 %) and "Teach-In" is started. Once the function has ended, the resistance value is determined and the function can be used. In "Teach-In" (Figure 33), 2 additional settings can be configured:

With "Automatically once", the resistance value is recalculated each time the power supply is switched on again.

With the setting "Automatically cyclical", the resistance value is recalculated every minute. This setting is particularly suitable for SiC heating elements and when the system is not switched off for a long time. With these elements, the resistance will change simply through the elements aging, despite the load point staying the same.

With heating elements whose resistance varies based on temperature, it is not possible to use the limit values from the documentation (like in Table 4). The following approach is viable in these cases: set a very high limit value for the load monitoring (100 % in Figure 34), define a typical setpoint value in manual mode, and carry out "Teach-In" manually. The respective current percentage deviation from the calculated "Teach-In" value can be displayed in the actuators. In the application, the deviation is determined for typical power controller setpoint values or requested power values.

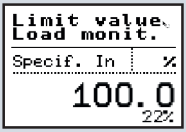


Figure 34: Information about the percentage deviation from the calculated "Teach-In" value (for example 22 %)

The limit value of the load monitoring (Figure 33) must be set higher than the maximum deviation that occurs (22 % in Figure 34). However, it may only be dimensioned as high that the monitoring is still activated if a heating element breaks. It may be that very large deviations from the previously calculated "Teach-In" value are detected (Figure 34). In these cases, the heating elements change their resistance significantly when the temperature changes and the function cannot be used for the application.

With the setting "Infrared radiator" under "Load type" (Figure 33), the load monitoring can also be used for short-wave infrared radiators.

The load monitoring can also be used for the 3-phase operation of loads with the JUMO TYA 202 or the JUMO TYA 203 thyristor power controllers (Figure 35).

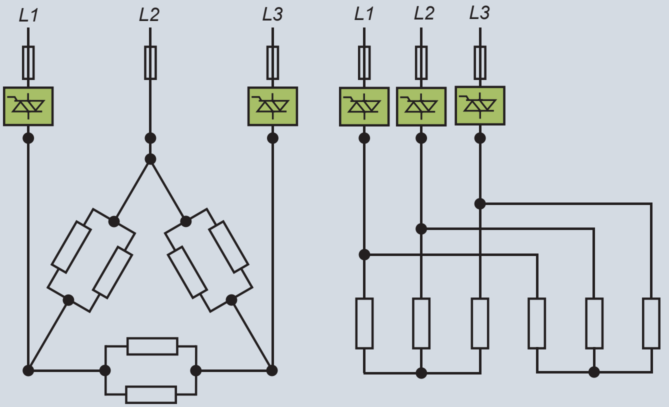


Figure 35: Connection of (in each case) 2 loads connected in parallel to the JUMO TYA 203 in delta or star connection

4.3.4 R-control (resistance limitation)

The surface temperature of molybdenum disilicide heating elements can be up to approx. 1800 °C. Due to the relatively low nominal voltage, the ceramic heating elements are normally operated using the JUMO IPC 300 electronic transformer, or the JUMO TYA 200 thyristor power controller and traditional transformer.

The elements are sensitive to excess temperature, so they have to be protected against overheating.

The heating elements have a positive temperature coefficient. In this way, an element resistance can be assigned to a limit temperature, which exists at this temperature (Figure 36).

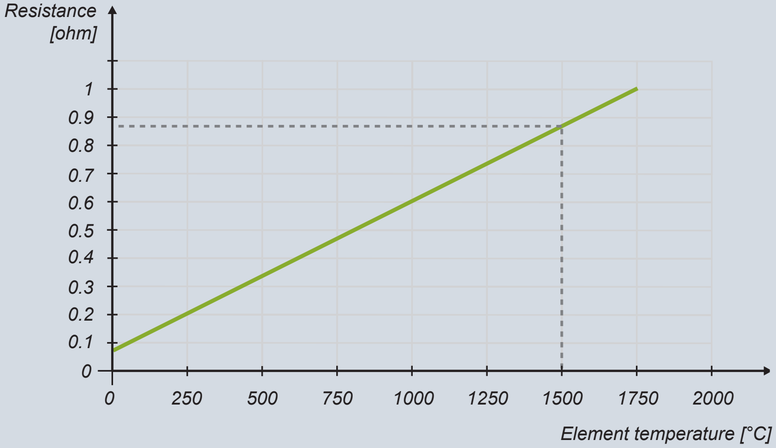


Figure 36: Resistance of a molybdenum disilicide heating element depending on the element temperature

The maximum load resistance (for example approx. 0.87 Ω) is entered directly in the JUMO IPC 300 / is defined in consideration of the ratio of the transformer in the JUMO TYA 200.

If the maximum load resistance is measured by the actuators, the output power is reduced and the resistance is adjusted to this value. The element resistance will not exceed the value that has been input / the temperature will be limited to the value associated with the resistance.

4.3.5 The inhibit input (input for the firing pulse inhibit)

The actuators have a binary input with which the load output is disconnected from the power. It is possible to configure whether the actuators are to be locked (with a HIGH or LOW signal).

After removing the firing pulse inhibit when the output level is simultaneously > 0, an actuator configured with a soft start function carries out the soft start again.

4.3.6 Operation of the actuators in a bus system

The actuators can be connected digitally via a serial interface or PROFINET, for example.

With the thyristor power controllers, the control electronics and the load circuit are supplied with the same voltage and switched using a main switch. If the load circuit is to be disconnected from the voltage supply, but the interface of the actuator is to remain active, an additional switch must be used (S2):

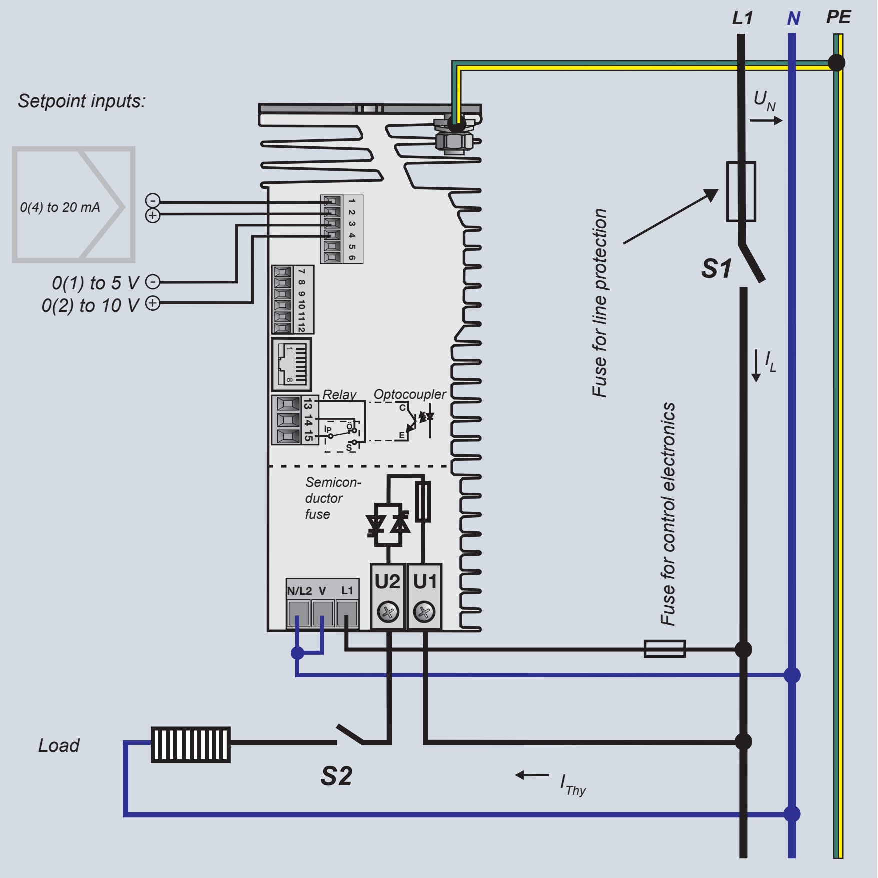


Figure 37: Use of an additional switch (S2) when using thyristor power controllers with field bus connection

Switch S2 is used to disconnect the load from the voltage supply. However, the control electronics continue to receive power and the interface remains active.

With the JUMO IPC 300 electronic transformer, it is not necessary to use an additional switch, as the control electronics are supplied via a separate voltage supply (DC 24 V). With the IPC, the switch for disconnecting the load from the power is located upstream of the network filter (see Figure 21).

With the JUMO TYA 200 and JUMO IPC 300, the load must be switched in a powerless state. This is carried out by the output level specification of the temperature controller (0 %). Alternatively, the inhibit input can be activated before the switching operation. After the switching operation, the inhibit function is removed again and the actuators are released again.

4.4 Special device functions of the thyristor power controllers

4.4.1 Dual energy management

Using this function, setpoint values of up to 50 % each can be preset on 2 power controllers, without causing current peaks in the network when they are switched on simultaneously. Even if the setpoint values are asymmetrically distributed (e.g. 30 % and 70 %), no current peaks are caused in the network.

To use this function, the 2 power controllers from the JUMO TYA 201 series must be connected to the same phase and the power controllers for the 3-phase loads – JUMO TYA 202 and JUMO TYA 203 – must be wired identically (see operating manual). The voltage supply for the devices is fed through a common switch and synchronization takes place by switching on at the same time. The power controllers must operate in burst-firing operation and a fixed cycle time of 500 ms must be set. Dual energy management always takes place for 2 power controllers. 1 of the 2 power controllers must be configured as device 1, and the other as device 2.

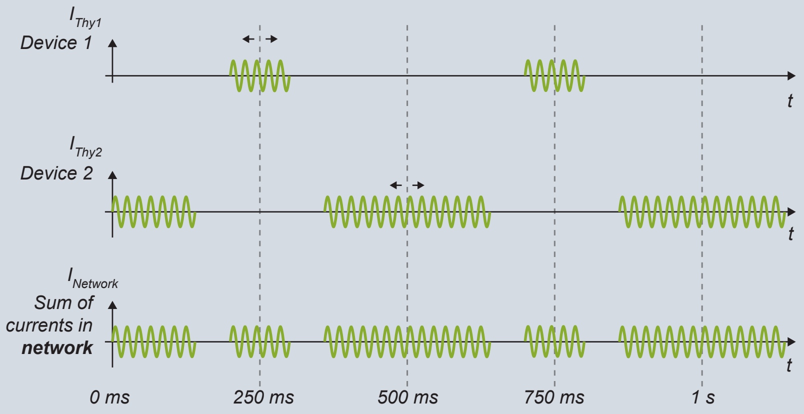


Figure 38: Dual energy management for 2 thyristor power controllers

The 2 power controllers switch on at different times. Starting from the dashed lines, the dispersion of energy takes place symmetrically to the left and right (see arrows). As long as the total output level of the 2 devices does not exceed 100 %, overlapping of the 2 device currents in a single phase is prevented. If the total output level exceeds 100 %, the energy management no longer has any effect.

4.4.2 Cutting the first half wave for transformer loads in burst-firing operation

When operating heating elements via a transformer, the iron of the transformer remains pre-magnetized after being switched off. If the thyristors are fired again, the iron becomes magnetically saturated with the first full half wave in burst-firing operation. The primary current is then, for the most part, only limited by the resistive part of the primary coil. In this case, the inrush current can be up to 50x the nominal current. This "rush effect" is counteracted in burst-firing operation by cutting the first half wave (α-start). For optimum adjustment to the transformer being used, the control angle is set for the first half wave of each pulse package (α-start = 0° el. to 90° el.).

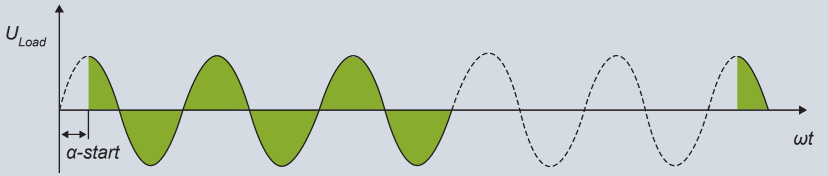


Figure 39: Cutting the first half wave for transformer loads in burst-firing operation

If the function is used in combination with the firing pulse inhibit, the first half wave is already cut following removal of the inhibit and if the output level is simultaneously > 0.

Instead of cutting the half wave, it can be expedient to use the soft start function with phase-angle control for operation of the transformer.

4.4.3 Using the thyristor power controllers as switches

Selecting the "Logic (switch)" setting under "SCR control" means that the power controller is used as a switch (Figure 40).

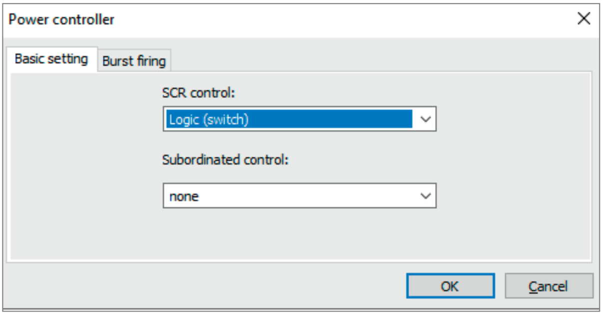


Figure 40: Setting for operating the power controllers as switches (configuration program)

Actuation is usually carried out via a binary input. As long as this input is closed, the thyristors are fired when passing the zero point of the mains voltage and not locked again until the input is opened.

In the case of transformer loads, the first mains voltage half wave must be cut before each pulse group. This can take place by configuring "Alpha default value" and entering a value.

The full power is switched by closing the binary input. If this is too high for the application, the output power can be reduced by cutting all of the sine waves ("Alpha default value"). The power controller then essentially behaves like in phase-angle operation, but is switched on and off via a binary input. The control angle can be fixed by the configuration or the variation is done by the signal at an analog input. It is also possible to use a potentiometer: in this case, the load is switched on and off by means of a binary signal, and the power varies at the potentiometer. Basically, when switching larger loads with a control angle larger than 0° el. the disadvantages of phase-angle operation must be taken into account.

4.4.4 Actuation of electromagnetic vibrators through half-wave control

Electromagnetic vibrators function as a drive in vibratory conveyors and vibrating screens, or are used for inductors in containers and bunkers (for example for releasing cement).

After selecting the operating mode "half-wave control," the 1-phase power controllers (JUMO TYA 201) give pulsating direct voltage to the vibrators. The positive half waves are switched on and off through actuation of the inhibit input. If the intensity of the half waves is too high, it can be reduced by cutting the half waves.

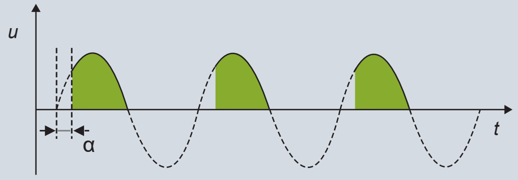


Figure 41: Half-wave control with phase-angle control

The cutting angle is specified via an analog input, for example via a potentiometer.

5 Operation of heating elements using a transformer

Heating elements with a nominal voltage that deviates significantly from the phase voltage or phase-to-phase voltage are operated using a transformer.

In most applications, this affects ceramic heating elements such as molybdenum disilicide heating elements (surface temperatures up to approx. 1800 °C) and silicon carbide heating elements (surface temperatures up to approx. 1600 °C).

5.1 Operation of molybdenum disilicide heating elements ($MoSi_2$)

Molybdenum disilicide heating elements (or their interconnection) have a smaller nominal voltage than the phase voltage or phase-to-phase voltage of the low-voltage networks. They have an extremely low cold resistance, but the resistance increases as the temperature increases. The elements must be protected against overheating (see also Chapter 4.3.4).

The high-temperature elements are connected directly to the **JUMO IPC 300 electronic transformer** (Figure 42).

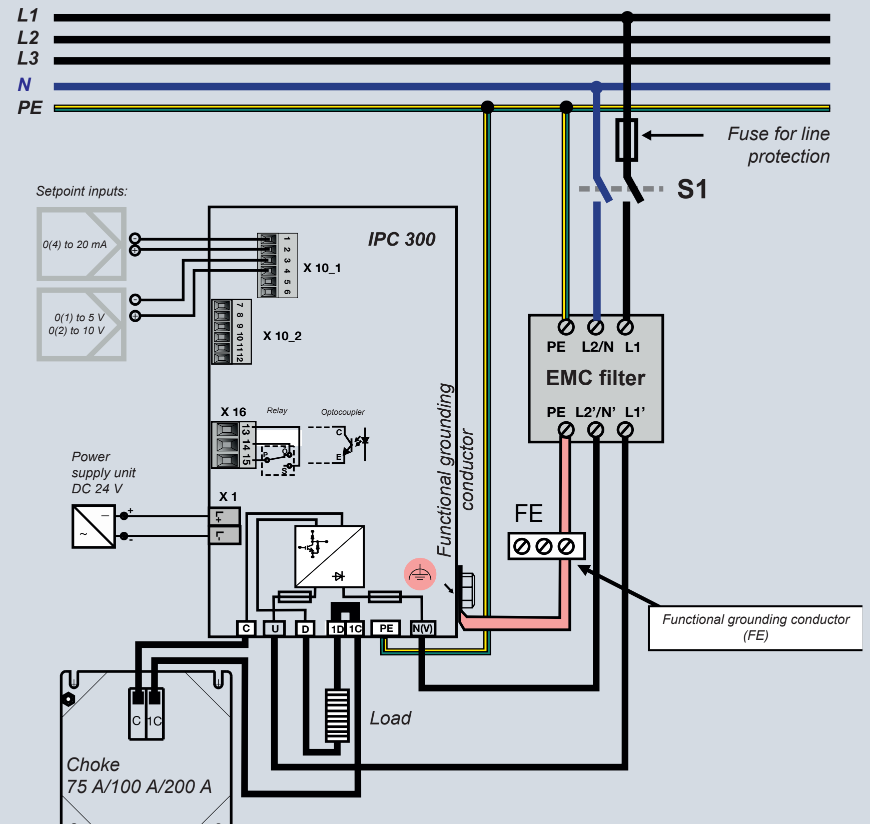


Figure 42: Direct connection of molybdenum disilicide heating elements to the JUMO IPC 300 electronic transformer

The JUMO IPC 300 requires a choke in the load circuit that corresponds to the load current, but there is no need for an external transformer. U^2 is selected as the subordinate control loop and the nominal voltage of the elements (or of all interconnected elements) is set as the maximum voltage. Due to the very low cold resistance of the elements, current limiting is necessary and R-control prevents the elements from overheating. As a result of the amplitude control, the percentage of harmonics is relatively low, and it is reduced even further by the filter which comes with the accessories.

In the case of the **JUMO TYA 200 thyristor power controllers**, the elements must be connected via an additional transformer:

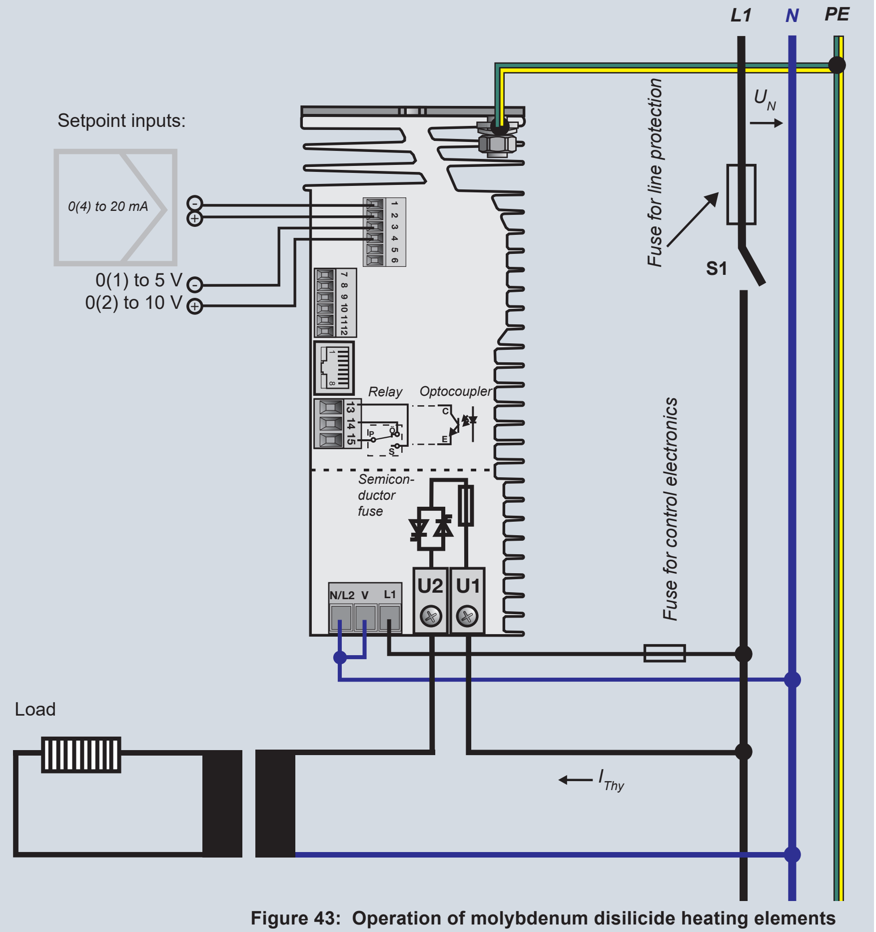


Figure 43: Operation of molybdenum disilicide heating elements using a thyristor power controller and transformer

In the example, the transformer transforms the phase voltage into the nominal voltage of the elements (Figure 43). When selecting the maximal values for the load voltage, the load current, and the resistance at the load output, it is important to always factor in the ratio of the transformer.

Due to the necessary current limiting, the power controllers must operate in phase-angle operation at least while the elements are heating up. This can be carried out by using the soft start function with phase-angle control, for example. If the transformer is dimensioned appropriately, in principle it is possible to use burst-firing operation after this. If the power controllers are to operate only in phase-angle operation, filters are required. Subsequently, in a typical working point, the control angle is not allowed to be too large, as otherwise the percentage of reactive power and percentage of harmonics are too high.

The JUMO TYA 202 and JUMO TYA 203 power controllers can also be used to operate 3-phase loads by means of a transformer.

5.2 Operation of silicon carbide heating elements (SiC)

The voltage also has to be transformed for SiC heating elements. Furthermore, their unusual characteristics and unique behavior over the long term require a particular type of control.

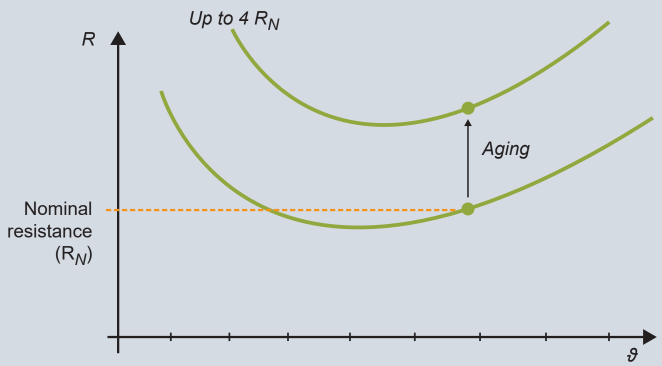


Figure 44: Temperature behavior of a SiC heating element

Figure 44 shows the temperature and long-term behavior of SiC heating elements. In a cold state, they have a relatively high resistance and therefore do not require current limiting. As the temperature increases, the resistance of the elements falls, until it finally starts increasing again. Furthermore, the resistance of these elements increases as they age by up to a factor of four.

The elements must output the nominal power during their entire operation time. Due to the way they behave, this is not possible with the common U^2 control. If the load voltage is selected so that the nominal power is generated in new elements ($P = U^2/R_N$), this results in just a quarter of the nominal power being produced with consumed elements for the same load voltage ($P = U^2/(4 \times R_N)$).

For these elements, the subordinate P control is used and the power that is to be output at 100 % output level is defined (Figure 45). In order to output the required power, the actuator must keep increasing the load voltage over the service time of the elements. If the resistance becomes too high, this means the heating elements are completely worn: even though the specified maximum load voltage is output, the system will no longer be able to achieve the required power. This behavior can be detected with SiC or control loop monitoring, which can help the user to know when to replace the elements.

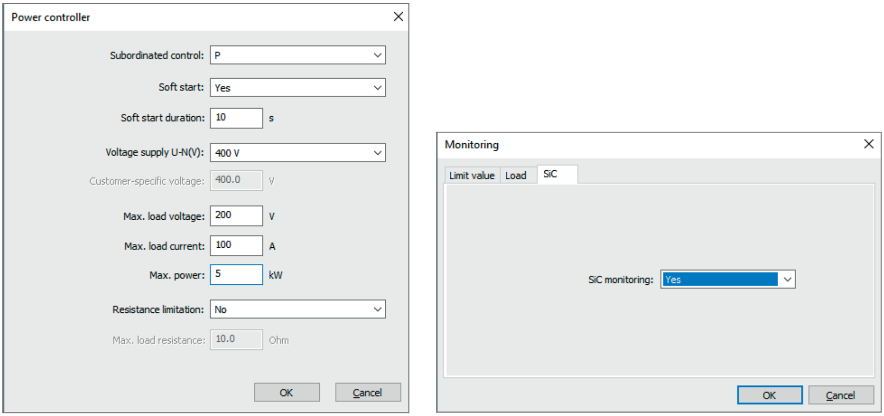


Figure 45: Example settings for a JUMO IPC 300 when using SiC heating elements (configuration program)

For example: P control is activated for a **JUMO IPC 300** and the maximum power is set to 5 kW (Figure 45). The load voltage is limited to 200 V. Without it being a compulsory requirement, the load current is limited to the input value (100 A) and the soft start function is activated for a "soft" startup. If the output level for the electronic transformer is 100 % for at least 15 minutes, but the JUMO IPC 300 can no longer output the required power despite the maximum load voltage, this is signaled by the SiC monitoring. The next time the system is shut down, the user will know that the elements need to be replaced.

SiC heating elements are also often connected in parallel. However, if 1 of the elements breaks, the P control supplies the intact elements with additional load. For example: 3 heating elements are in use and the setpoint value is 4.5 kW. Each heating element converts 1.5 kW of electrical energy into thermal energy. If 1 of the elements breaks, the actuator will continue trying to supply the total power of 4.5 kW. If the voltage reserve is large enough, each of the remaining elements is supplied with a load of 2.25 kW. In a worst case scenario, the heating elements will be destroyed.

The JUMO IPC 300 is able to protect the remaining elements through the use of 2 external current sensors (Figure 46).

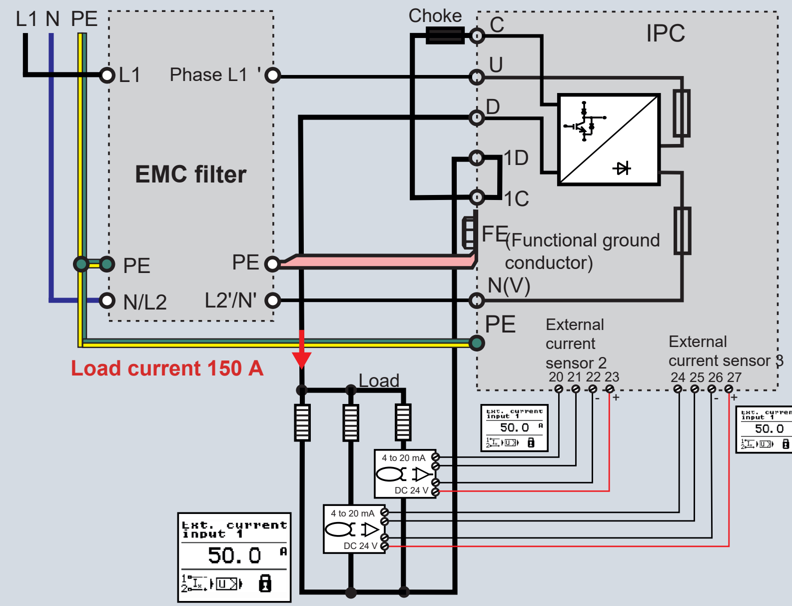


Figure 46: Connection of 2 external current sensors to the JUMO IPC 300 to protect the heating elements when using P control

In 2 of the 3 load strands (Figure 46), current sensors are installed which feedback the respective current to the transformer via a 4 to 20 mA signal. Furthermore, the total load current is always measured with the JUMO IPC 300, which means that the current in the first branch can also be determined. If a heating element breaks, the transformer reduces the load voltage such that no more than a third of the required power is output in each branch (in the case of symmetrical load distribution). This approach ensures that, if an element breaks, the remaining elements are not supplied with any additional load.

Operating SiC heating elements with a **thyristor power controller** requires the use of a transformer with several taps (Figure 47).

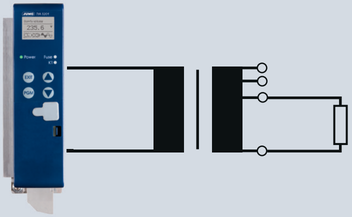


Figure 47: Operation of SiC heating elements using a transformer with several taps

The power controllers usually operate in phase-angle operation, use the subordinate P control loop, and make use of control loop monitoring.

If the system is put into operation with new elements, the lower tap is used. Only a relatively small control angle is used to output the required nominal power (if the control angles are too large, the percentage of control reactive power and the percentage of harmonics would be too high). Given that the resistance of the elements increases, over the course of their use, the load voltage must keep being increased; this is achieved by cutting the mains voltage with ever smaller control angles. Although the control angle will be 0° el. after a certain amount of operation time, the system will no longer be able to output the required power. This is signaled by the control loop monitoring, and at the next opportunity, the load at the transformer must be rewired to the middle tap.

Actuation takes place again with a control angle of > 0° el., and there is a voltage reserve again. The required control angle becomes smaller again over the course of the operation time until, at 0° el., the third tap has to be used.

Once it is no longer possible to output the power using the upper tap, the control loop monitoring signals this again and the elements have to be replaced.

The transformer must be configured for the current that flows when using the new, relatively low-resistance elements. The voltage at the upper tap must correspond to around twice the voltage value of the lower tap.

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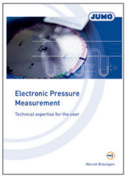

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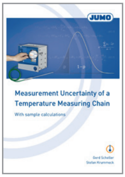

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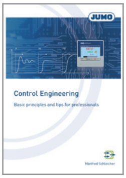

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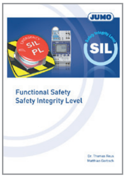

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