Understand your Heat Process Problems and how PID Control deals with them.

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Some processes are easy to control and an ON-OFF controller will do a good job. Other processes come in varying degrees of complexity, size and mass and can be very hard to control.

An easy process to control would be a well stirred water bath with a small gage electric heater and a fast, bare thermocouple.

You could use an ON/OFF controller which has a very small dead band (defined as switch-off temperature when rising minus switch-on temperature when falling).

As soon as the temperature rises to set point the control relay opens and the temperature stops climbing. When the temperature falls slightly, say 0.1 º C, the controller switches the heater on again. After reaching set point the temperature graph is virtually a straight line.

Why so easy? Although the heater wire could be much hotter than the water it has low mass and heat capacity and cannot deliver a noticeable temperature overshoot after switch-off. Also the thermocouple senses temperature changes immediately and wastes no time in telling the controller to switch off. This is not a practical process but it shows that low thermal capacity (not low power) of the heat source plus fast response of the temperature sensor make for easy control.

A real water bath; not so easy.

A practical heater will be more robust, have a heavy metal sheath and could run one or two hundred ºC higher than the water temperature. Controller switch-off when the temperature indication reaches set point does not stop the stored heat in the heater being released into the water. Overshoot is inevitable. Worse yet; a real thermocouple will be insulated and in a protection tube so it is late sensing that the water temperature has come up to the set point. By this time the water is already above set point so the temperature cycles continually above and below set point even though the controller is very precise in switching on and off exactly at set point.

A plastics extruder barrel zone.

Here there is a massive heater and barrel wall running hotter than the polymer when heat is being demanded. Also the thermocouple tip has to be set deep, away from the heater, because you are sensing and controlling the polymer temperature. This makes the thermocouple late in responding to changes in heat input and reporting back to the controller. ON/OFF control would give severe overshoot and temperature cycling.

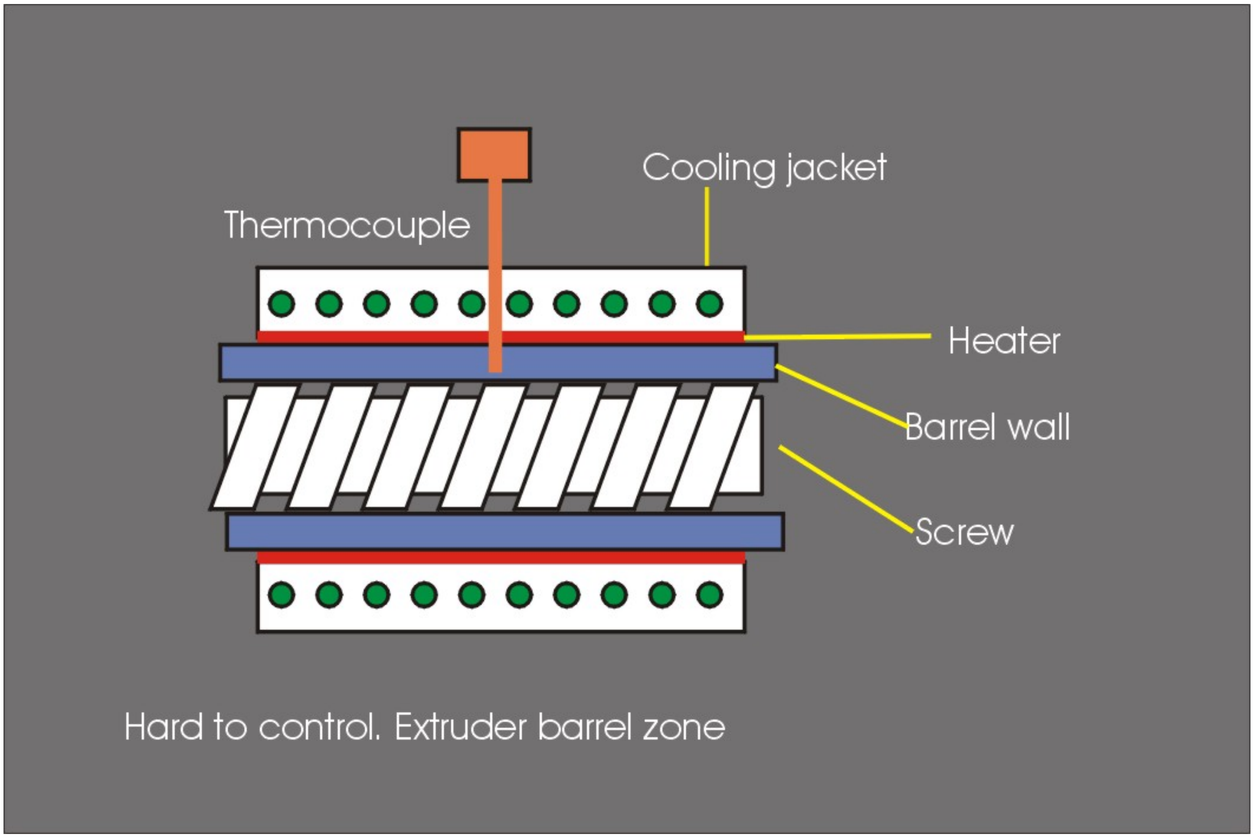

Fig 2. Extruder Barrel Zone

These examples point to thermal time lag as the enemy. While lag is usually unavoidable in a practical process, always be open to ways of reducing it. Example: under your milk saucepan you may have a heavy electric hob. Switch off does not avoid boil over. Change to a gas ring or a tungsten-in-quartz heater; neither one has much thermal mass to devote to a boil over after you have switched off.

Go for the fastest practical sensor. Light gage or even exposed thermocouples. Optical pyrometers are even faster.

What kind of controller handles the above problems?

Consider a controller that can throttle back the heater power well ahead of the temperature reaching set point. That is, make the power shrink in proportional to distance from set point. The controller now has a chance to anticipate and head off overshoot and temperature cycling. This action defines it as a proportional controller. Fig 3 shows the elements of such a controller along with its thermocouple and a controlled heater.

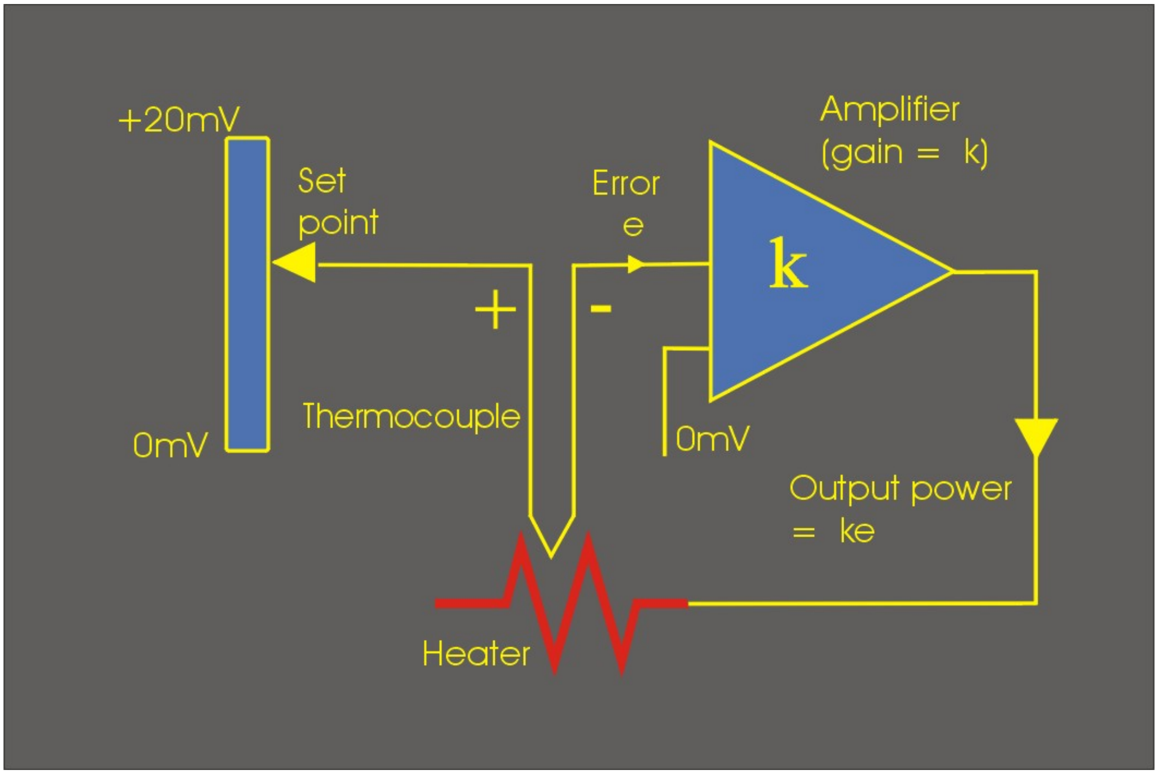

Fig 3. Simple controller circuit with thermocouple and load

Proportional control, how it works (Refer to Figs 3 and 4)

On the circuit on Fig 3 you adjust the set point by setting a dc millivolt signal representing desired temperature. It is shown here as a potentiometer but is more usually generated electronically. You read the set point on a temperature scale or on a digital readout. The millivolt output (feedback) of your control thermocouple will match the set point when the process comes up to the desired temperature.

The back-to-back (subtractive) connection of set point millivolts and thermocouple millivolts puts the difference (called the error signal e) into the amplifier. As connected here, the amplifier's objective is to deliver enough power to the heater to bring the thermocouple millivolts, therefore temperature, up to match the set point.

If the amplifier gain is high, the slightest error signal, minus or plus at its input brings about respectively full heater power or no heater power. You are now back to ON/OFF control, overshoot and temperature cycling. To achieve the anticipation and power throttleback needed for stability you can reduce the amplifier gain k so that it takes an error e of say 20º to give full heater power at the output. Being a linear amplifier in terms of power, a 10º error gives 50% power, 5º gives 25% power and so on.

The controller is now delivering corrective action (i.e. heater power) in proportion to deviation of temperature from set point. This is PROPORTIONAL CONTROL.

Power P = ke (that is, amplifier gain x error)

The size of error needed to make the amplifier deliver 100% power is called PROPORTIONAL BAND (40º in this example). It is sometimes expressed as a percentage of controller temperature range. So if this controller has a range of say 0 to 1000 deg, 40 deg represents a 4% proportional band. The gain k is defined as 100 divided by the % proportional band (100/4 = 25 in this example)

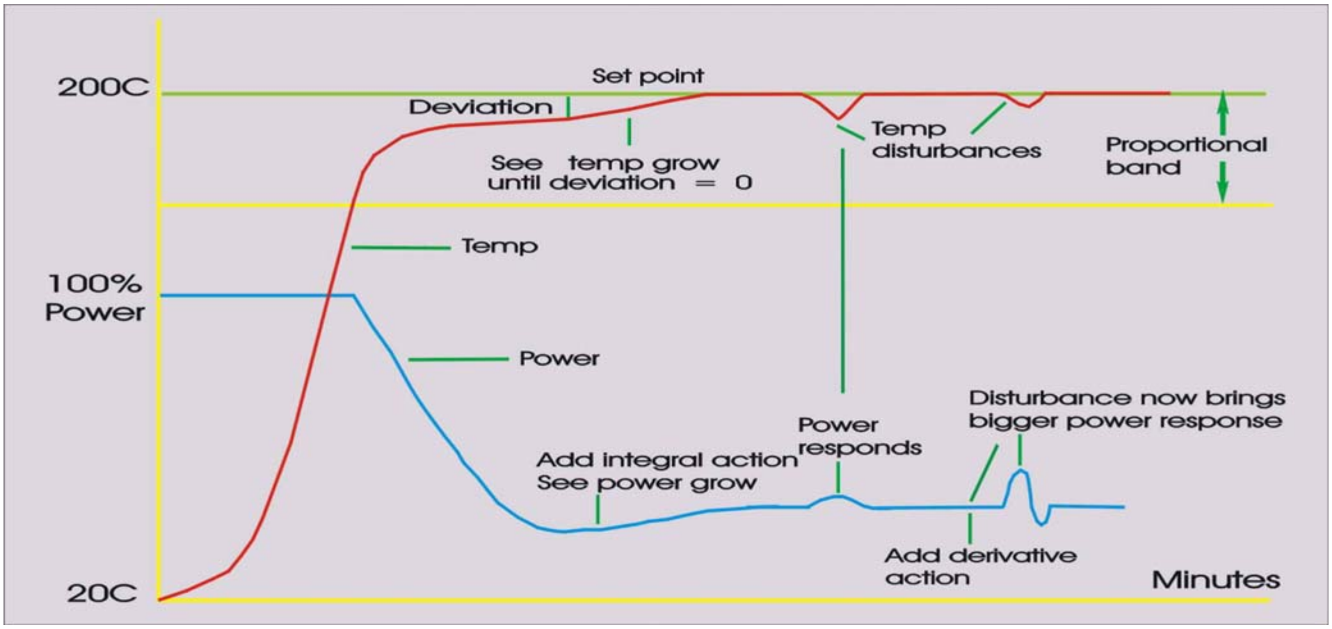

Fig 3. Start up Graph of a Temperature Control Loop

How to avoid overshoot and temperature cycling

If you make the proportional band large enough as shown in Fig 2, the power will throttle back early enough to avoid overshoot and temperature cycling.

If the temperature could reach set point, the deviation (which is the amplifier input) would reach zero therefore so would the power. This does not happen. The temperature settles out some way below set point and some intermediate level of power is delivered.

This shortfall of temperature below set point is called offset. You could reduce the proportional band (more amplifier gain) to get more power and try to reduce the offset but you risk breaking into temperature cycling again, (called control loop instability).

How to eliminate offset

Say the temperature settles at 180ºC, i.e. 20º below your set point of 200 with a corresponding power of 50%.

You could reset the set point to about 222 to get the controlled temperature to come up close to 200. Some simple controllers have a small knob labelled MANUAL RESET which achieves this without it showing as an extra 22 deg on the set point display.

This 22 deg deviation is amplified into enough power to heat the zone to about 200º. Problem; there may be times when the process needs say, twice that power to hold 200 deg;

for example when the process has a higher material throughput. To put out twice the power, the amplifier would need twice the input (about 44º offset) otherwise the temperature would head down again towards 180º.

Integral action (sometimes called automatic reset)

Are you going to keep resetting the set point and waiting around every time the heat demand changes? No, you need an automatic and continuous watch on the temperature and automatic power adjustments, aimed at keeping the deviation at zero. So let the amplifier do this as a second job. Let it watch the deviation and so long as it persists let the amplifier put out a gently increasing contribution until there is just enough power to make the deviation

e equal to 0. (See power growth on Fig 3).

The amplifier is designed to make the rate of power growth proportional to deviation. So when temperature is close to set point the power is changing very slowly until at set point the power stops growing and holds at just the level needed to hold the temperature at set point. For deviations above set point the integral action gently reduces power to achieve zero deviation.

This is called INTEGRAL ACTION. You now have a PI (proportional + integral) controller.

How to define integral time

The strength of integral action is expressed in terms of integral time, usually seconds or minutes.

If the deviation = one PROPORTIONAL BAND the contribution of integral action will grow to 100% power in one INTEGRAL TIME Ti.

Note that a short integral time brings a fast growth of power and an eager corrective action.

Some manufacturers express integral action in terms of REPEATS PER MINUTE, defined as the reciprocal of integral time. This leads one to expect some kind of repetitive action, which it is not; or to confuse it with cycles of control loop instability and even with cycles of a time-proportioning controller output. Best to not use the term.

Derivative action, sometimes called rate action

Now give the amplifier a third job. Let it watch for CHANGES of temperature and put out a contribution of power proportional to RATE OF CHANGE of temperature. E.g. fast dive, big power boost, slow dive gentle boost, fast rise big throttle back etc. The purpose here is to resist and damp out unwanted changes and to speed up recovery from temperature disturbances as shown in Fig 3. This contribution to output power exists only when the temperature is changing.

How to define derivative time

If the temperature dives at a rate of one proportional band in one DERIVATIVE TIME Td, the contribution of derivative action is 100% power (and minus 100% power for temperature climbing)

You now have a PID (proportional + integral + derivative) controller. Also called a 3-term or

3-mode controller.

To optimize (= tune) your controller you adjust the PID settings and sometimes other parameters to obtain the control response that best fits the process.

Start up overshoot

Say that a 10deg proportional band gives you the tight, stable control that you want after the process has settled down but power throttles back too late to avoid overshoot on start up. You could increase proportional band and that would help; but then you lose that tight control that you worked to achieve.

You could design the controller to introduce a pause at say 20 deg before set point. That is, move the proportional band temporarily downwards 20 deg. The controller now throttles back the power that much sooner, then slowly takes the proportional band upwards to its normal position at a speed related to integral time. This gives you a new adjustable parameter called LOW CUTBACK, set to 20 deg in this example.

Analogy. When you drive to a junction, ease up 200 ft away (low cutback) then brake for the last100 ft (proportional band).

If you notice a start up overshoot, try a LOW CUTBACK setting equal to or somewhat greater than the amount of overshoot. **Note. T**his parameter name and means of implementation varies with manufacturer.

Self tuning

Many controllers have a feature called **self-tune** or **automatic tune**. Upon initiating this feature the controller typically gives a controlled dose of heat to the process and from the temperature response back from the process, calculates optimum settings for the PID parameters and sometimes other parameters. Record these after a successful self tune.

Self tuning can take anything from a minute or two in the case of a fast tungsten lamp applying heat to a low mass material to one hour or more with a slow, large mass process.

It is advisable to start self tune when the process is at or a bit lower than its normal working temperature. Watch the temperature at this stage and be ready to intervene if the initial heat dose threatens to overheat your material or equipment. You must make your own judgements of optimum control. E.g. if your processed material takes no harm from a certain overshoot you might accept that in exchange for a faster time to settle at set temperature.

Manual tuning

You may prefer to tune manually or try to improve on your controller's results with your own perception of optimum. Refer to the procedure in the controller manufacturer's manual. If you have no instruction manual use the following procedure.

Turn integral and derivative action off. Put the set point at or a bit below your working temperature. Start with a proportional band that gives temperature stability (try a proportional band say 10% of working temperature). Reduce the setting and wait. Do it again and again until you find a value (call it P) where you just begin to see regular slow temperature swings. Note the time T between successive peaks of temperature (this is typically 5 to 15 min). Set integral time equal to T/2. Set derivative time equal to T/8. Set proportional band to 1.7P.

Keep the following points in mind.

A too small proportional band gives temperature cycling (control loop instability).

A too large proportional band gives sluggish control, (a too feeble change of power in response to deviations of temperature).

A too small integral time will give an over eager response and result in instability.

A too large integral time will slow down both the approach to set point on a start up and return to set point after a disturbance.

Although derivative action helps to achieve stability a too large derivative time can also bring instability by an over eager power boost or throttle back.

How the controller varies power to the heater

We referred to the controller amplifier putting out power to the heater. The curve in Fig 2 shows a continuous modulation of power. This could occur, for example with a silicon controlled rectifier unit (SCR) in the phase-angle mode delivering heater power by smooth variation of ac voltage like a lamp dimmer.

There are too many output devices (called final control elements) to cover here so we will look at just one widely used method referred to as TIME-PROPORTIONING CONTROL.

With electric heat the usual method is to make the controller pulse a magnetic contactor, typically once every 10 seconds. See Fig 4.

This is called CYCLE-TIME and not to be confused with the temperature cycling of an unstable control loop.

The controller delivers long pulses for high power and short pulses for low power while keeping the same time (10 seconds) between the start of successive pulses. The same idea works on an electric cooker hob; turn the knob half way round and the contact closes for 5 sec then opens for 5 sec continually. This makes your 2 kW hob deliver an average power of 1kW.

The temperature controller determines the duration of the pulses. Although it can only turn the power ON or OFF it is called a TIME-PROPORTIONING not an ON/OFF controller.

ON/OFF implies switch on or off occurring only when the temperature crosses set point.

A time-proportioning controller turns the power progressively lower by ever shorter ON pulses as the temperature comes up towards the set point. The pulses then have just the right duration to hold the temperature at set point.

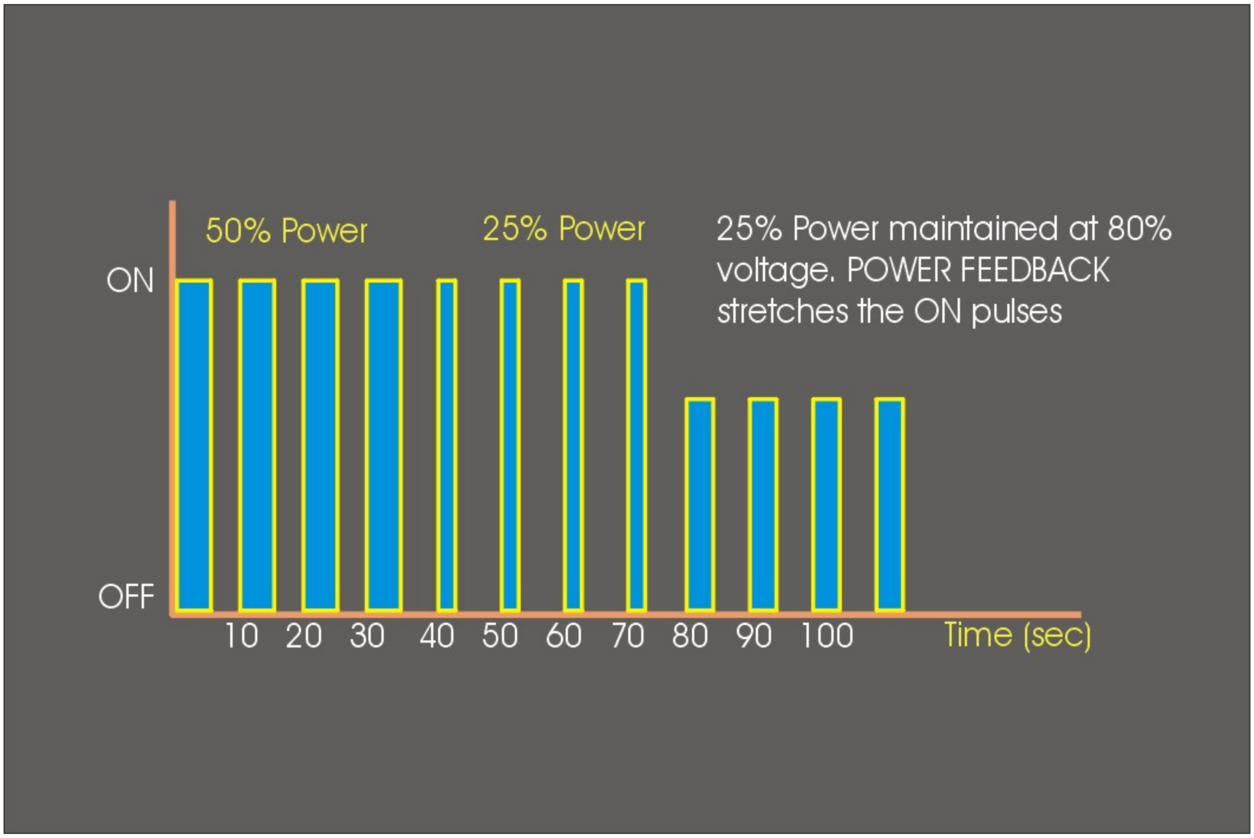

Fig 4. Modulation of power by pulse width variation

Power feedback

Say your process is running at 25% power and the temperature is right on set point. Let the line voltage fall by 20%. This results in a heater power drop of 36% because of the square law dependence of power on voltage. Sooner or later the temperature falls. After a time, the thermocouple and controller would sense this fall and increase the ON-TIME of the contactor just enough to bring the temperature back to set point. Meanwhile the material is running a bit cooler than optimum and may show some imperfection in the product.

Some smart controllers watch line voltage continuously and increase or decrease contactor percentage ON-TIME to compensate right away. In this way the process need never suffer a temperature disturbance caused by a line voltage change. See Fig 4.

Note that this feature, called POWER FEEDBACK, is only applicable to electric heaters. Disable it if you have some other heating medium such as gas, steam or heat transfer oil. In process control terminology the same idea, heading off a disturbance as soon as it threatens, is called FEEDFORWARD. For example you might vary the base heater power on a conveyer furnace automatically in proportion to material throughput and leave the controller to do only fine trimming.

Choice of cycle time

Cycle time is a controller parameter with a range adjustable typically between 0.1 and 100 sec. On many processes there is so much metal and material mass that you could set the cycle time to 20 or more seconds and the temperature would not rise and fall noticeably in sympathy with these slow pulses. A magnetic contactor would survive this duty well enough.

On the other hand consider a fast responding process like radiant heating and optical temperature sensing of a moving web. A 20 sec cycle time would show large temperature swings and confuse the controller. Make sure you recognize this as a too long cycle time, not control loop instability. Here you would set a cycle time of typically 0.2 sec to avoid the alternate under and overheated sections of web that slow cycling would give. You would also use a solid-state contactor because a magnetic one would soon be destroyed.

If you were using tungsten lamp heaters say for short wave infrared heating, you would normally use silicon controlled rectifiers with phase-angle control. This lets you set the power level appropriate to your optimum wavelength for the heated material .As a bonus you can by use of **current limit** and **soft start** features, defeat the high inrush current and fuse blowing threatened by the very low cold resistance of tungsten. Lately solid state contactors with zero cross switching and ON times as low as a half cycle of the 60Hz supply have been used in these applications, bringing cost and low RF interference advantages.

Conclusion

There are many other tricks and logic interventions built into modern controllers. They are too many and complex to cover here and their names differ according to manufacturer. Take the time to understand your process and every feature that your controller offers. Resist the temptation to park your brain and leave control quality to some controller magic that is not clearly specified.

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