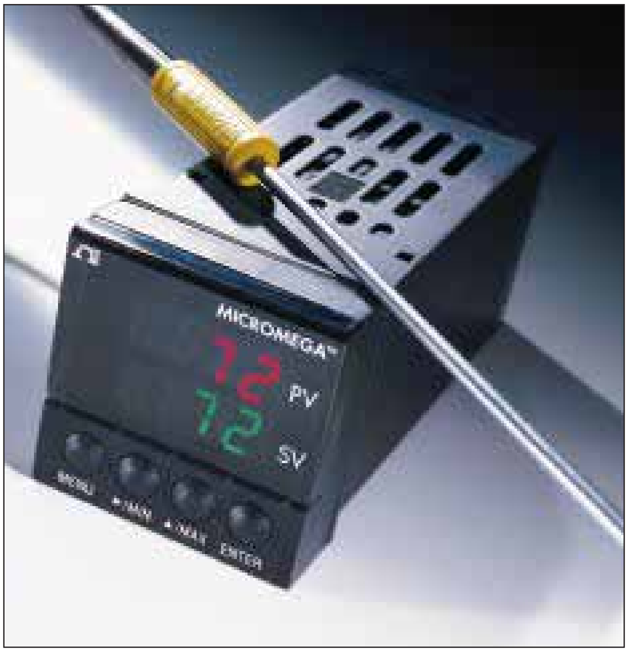
Introduction To Temperature Controllers



The Miniature CN77000 is a full featured microprocessor-based controller in a 1/16 DIN package.

How Can I Control My Process Temperature Accurately and Reliably?

To accurately control process temperature without extensive operator involvement, a temperature control system relies upon a controller, which accepts a temperature sensor such as a thermocouple or RTD as input. It compares the actual temperature to the desired control temperature, or setpoint, and provides an output to a control element.

The controller is one part of the entire control system, and the whole system should be analyzed in selecting the proper controller. The following items should be considered when selecting a controller:

1. Type of input sensor (thermocouple, RTD) and temperature range
2. Type of output required (electromechanical relay, SSR, analog output)
3 Control algorithm needed (on/off, proportional, PID)
4 Number and type of outputs (heat, cool, alarm, limit)

What Are the Different Types of Controllers, and How Do They Work?

There are three basic types of controllers: on-off, proportional and PID. Depending upon the system to be controlled, the operator will be able to use one type or another to control the process.

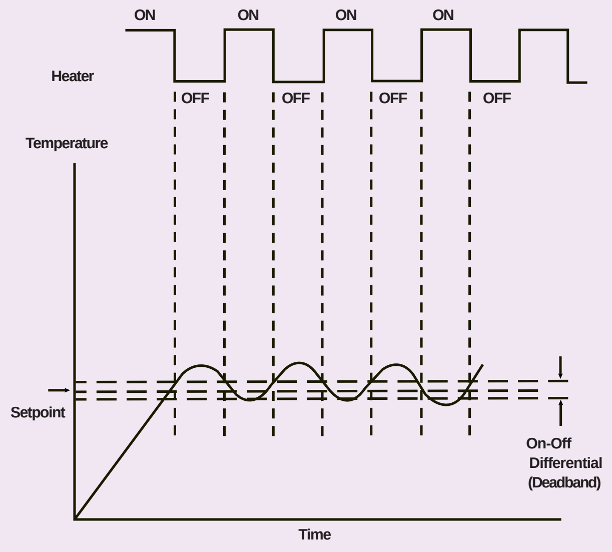
On/Off

An on-off controller is the simplest form of temperature control device. The output from the device is either on or off, with no middle state. An on-off controller will switch the output only when the temperature crosses the setpoint. For heating control, the output is on when the temperature is below the setpoint, and off above setpoint.

Since the temperature crosses the setpoint to change the output state, the process temperature will be cycling continually, going from below setpoint to above, and back below. In cases where this cycling occurs rapidly, and to prevent damage to contactors and valves, an on-off differential, or “hysteresis,“ is added to the controller operations. This differential requires that the temperature exceed setpoint by a certain amount before the output will turn off or on again. On-off differential prevents the output from “chattering” (that is, engaging in fast, continual switching if the temperature’s cycling above and below the setpoint occurs very rapidly).

On-off control is usually used where a precise control is not necessary, in systems which cannot handle the energy’s being turned on and off frequently, where the mass of the system is so great that temperatures change extremely slowly, or for a temperature alarm.

One special type of on-off control used for alarm is a limit controller. This controller uses a latching relay, which must be manually reset, and is used to shut down a process when a certain temperature is reached.

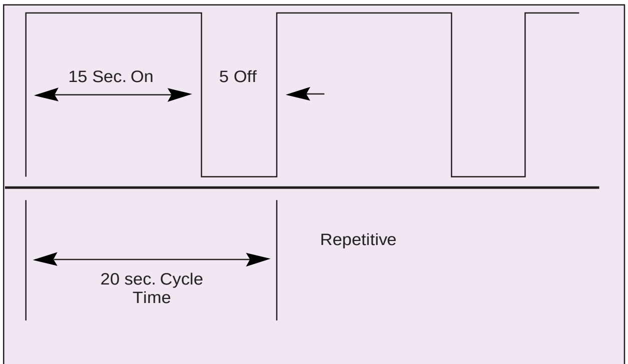


ON/Off Temperature Control Action

Introduction To Temperature Controllers Cont'd

Proportional

Proportional controls are designed to eliminate the cycling associated with on-off control. A proportional controller decreases the average power being supplied to the heater as the temperature approaches setpoint. This has the effect of slowing down the heater, so that it will not overshoot the setpoint but will approach the setpoint and maintain a stable temperature. This proportioning action can be accomplished by turning the output on and off for short intervals. This "time proportioning " varies the ratio of 'on' time to 'off' time to control the temperature. The proportioning action occurs within a "proportional band" around the setpoint temperature. Outside this band, the controller functions as an on-off unit, with the output either fully on (below the band) or fully off (above the band). However, within the band, the output is turned on and off in the ratio of the measurement difference from the setpoint. At the setpoint (the midpoint of the proportional band), the output on:off ratio is 1:1; that is, the on-time and off-time are equal. If the temperature is further from the setpoint, the on- and off-times vary in proportion to the temperature difference. If the temperature is below setpoint, the output will be on longer; if the temperature is too high, the output will be off longer.



Time Proportioning at 75% Output Level

The CN2010 controller features ramp and soak, the ability to control temperature over time.

The proportional band is usually expressed as a percent of full scale, or degrees. It may also be referred to as gain, which is the reciprocal of the band. Note, that in time proportioning control, full power is applied to the heater, but is cycled on and off, so the average time is varied. In most units, the cycle time and/or proportional band are adjustable, so that the controller may better match a particular process.

In addition to electromechanical and solid state relay outputs, proportional controllers are also available with proportional analog outputs, such as 4 to 20 mA or 0 to 5 Vdc. With these outputs, the actual output level is varied, rather than the on and off times, as with a relay output controller.

One of the advantages of proportional control is simplicity of operation. It may require an operator to make a small adjustment (manual reset) to bring the temperature to setpoint on initial startup, or if the process conditions change significantly.

Time Proportional				4-20 mA Proportional	
Percent On	On Time Seconds	Off Time Seconds	Temp (ºF)	Output Level	Percent Output
0.0	0.0	20.0	over 540	4 mA	0.0
0.0	0.0	20.0	540.0	4 mA	0.0
12.5	2.5	17.5	530.0	6 mA	12.5
25.0	5.0	15.0	520.0	8 mA	25.0
37.5	7.5	12.5	510.0	10 mA	37.5
50.0	10.0	10.0	500.0	12 mA	50.0
62.5	12.5	7.5	490.0	14 mA	62.5
75.0	15.0	5.0	480.0	16 mA	75.0
87.5	17.5	2.5	470.0	18 mA	87.5
100.0	20.0	0.0	460.0	20 mA	100.0
100.0	20.0	0.0	under 460	20 mA	100.0

Proportional Bandwith

Example: heating
Setpoint: 500˚F
Proportional Band: 80˚F
(±40˚F)

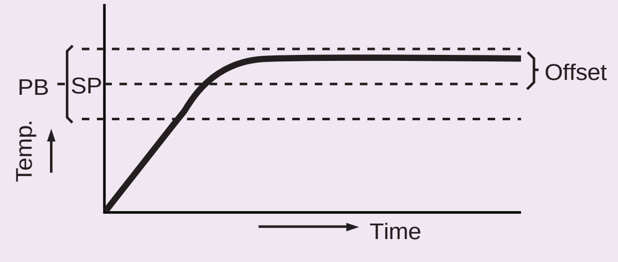
Systems that are subject to wide temperature cycling will also need proportional controllers. Depending upon the process and the precision required, either a simple proportional control or one with PID may be required.

Processes with long time lags and large maximum rate of rise (*e.g.*, a heat exchanger), require wide proportional bands to eliminate oscillation. The wide band can result in large offsets with changes in the load. To eliminate these offsets, automatic reset (integral) can be used. Derivative (rate) action can be used on processes with long time delays, to speed recovery after a process disturbance.

There are also other features to consider when selecting a controller. These include auto- or self-tuning, where the instrument will automatically calculate the proper proportional band, rate and reset values for precise control; serial communications, where the unit can “talk” to a host computer for data storage, analysis, and tuning; alarms, that can be latching (manual reset) or non-latching (automatic reset), set to trigger on high or low process temperatures or if a deviation from setpoint is observed; timers/event indicators which can mark elapsed time or the end/beginning of an event. In addition, relay or triac output units can be used with external switches, such as SSR solid state relays or magnetic contactors, in order to switch large loads up to 75 A.

PID

The third controller type provides proportional with integral and derivative control, or PID. This controller combines proportional control with two additional adjustments, which helps the unit automatically compensate for changes in the system. These adjustments, integral and derivative, are expressed in time-based units; they are also referred to by their reciprocals, RESET and RATE, respectively.



Process with Temperature Offset

The proportional, integral and derivative terms must be individually adjusted or “tuned” to a particular system, using a “trial and error” method. It provides the most accurate and stable control of the three controller types, and is best used in systems which have a relatively small mass, those which react quickly to changes in energy added to the process. It is recommended in systems where the load changes often, and the controller is expected to compensate automatically due to frequent changes in setpoint, the amount of energy available, or the mass to be controlled.

What Do Rate and Reset Do, and How Do They Work?

Rate and reset are methods used by controllers to compensate for offsets and shifts in temperature. When using a proportional controller, it is very rare that the heat input to maintain the setpoint temperature will be 50%; the temperature will either increase or decrease from the setpoint, until a stable temperature is obtained. The difference between this stable temperature and the setpoint is called offset. This offset can be compensated for manually or automatically. Using manual reset, the user will shift the proportional band so that the process will stabilize at the setpoint temperature. Automatic reset, also known as integral, will integrate the deviation signal with respect to time, and the integral is summed with the deviation signal to shift the proportional band. The output power is thus automatically increased or decreased to bring the process temperature back to setpoint,

The rate or derivative function provides the controller with the ability to shift the proportional band, to compensate for rapidly changing temperature. The amount of shift is proportional to the rate of temperature change.

A PID, or three-mode controller, combines the proportional, integral (reset) and derivative (rate) actions, and is usually required to control difficult processes. These controllers can also be made with two proportional outputs, one for heating and another for cooling. This type of controller is required for processes which may require heat to start up, but then generate excess heat at some time during operation.

What are the Different Output Types That Are Available for Controllers?

The output from the controller may take one of several forms. The most common forms are time proportional and analog proportional. A time proportional output applies power to the load for a percentage of a fixed cycle time. For example, with a 10 second cycle time, if the controller output were set for 60%, the relay would be energized (closed, power applied) for 6 seconds, and de-energized (open, no power applied) for 4 seconds. Time proportional outputs are available in three different forms: electromechanical relay, triac or ac solid state relay, or a dc voltage pulse (to drive an external solid state relay). The electromechanical relay is generally the most economical type, and is usually chosen on systems with cycle times greater than 10 seconds, and relatively small loads.

An ac solid state relay or dc voltage pulse are chosen for reliability, since they contain no moving parts. Recommended for processes requiring short cycle times, they need an additional relay, external to the controller, to handle the typical load required by a heating element. These external solid state relays are usually used with an ac control signal for ac solid state relay output controllers, or with a dc control signal for dc voltage pulse output controllers.

An analog proportional output is usually an analog voltage (0 to 5 Vdc) or current (4 to 20 mA). The output level from this output type is also set by the controller; if the output were set at 60%, the output level would be 60% of 5 V, or 3 V. With a 4 to 20 mA output (a 16 mA span), 60% is equal to (0.6 x 16) + 4, or 13.6 mA. These controllers are usually used with proportioning valves or power controllers.

What Should I Consider When Selecting a Controller for My Application?

When you choose a controller, the main considerations include the precision of control that is necessary, and how difficult the process is to control. For easiest tuning and lowest initial cost, the simplest controller which will produce the desired results should be selected.

Simple processes with a well matched heater (not over- or undersized) and without rapid cycling can possibly use on-off controllers. For those systems subject to cycling, or with an unmatched heater (either over- or undersized), a proportional controller is needed.

Temperature Controllers

Selection Considerations

CONTROLLABILITY OF ELECTRIC HEAT

The basic function of a controller is to compare the actual temperature with its setpoint and produce an output which will maintain that setpoint.

The controller is one part of the entire control system, and the whole system should be analyzed in selecting the proper controller. The following items should be considered when selecting a controller.

1. Type of input sensor (thermocouple, RTD, card and temperature range).
2. Placement of sensor
3. Control algorithm needed (on/off, proportional, PID, autotune PID)
4. Type of output hardware required (electromechanical relay, SSR, analog output signal)
5. Additional outputs or requirements of system (display required of temperature and/or setpoint, cooling outputs, alarms, limit, computer communication, etc.)

TYPE OF INPUT

The type of input sensor will depend on the temperature range required, the resolution and accuracy of the measurement required, and how and where the sensor is to be mounted.

PLACEMENT OF THE SENSOR

The correct placement of the sensing element with respect to the work and heat source is of the utmost importance for good control. If all three can be located in close proximity, a high degree of accuracy, up to the limit of the controller, is relatively easy to achieve. However, if the heat source is located some distance from the work, widely different accuracies can be obtained just by locating the sensing element at various places between the heater and the work.

Before selecting the location for the sensing element, determine whether the heat demand will be predominantly steady or variable. If the heat demand is relatively steady, placement of the sensing element near the heat source will hold the temperature change at the work to a minimum.

On the other hand, placing the sensing element near the work, when heat demand is variable, will enable it to more quickly sense a change in heat requirements. However, because of the increase in thermal lag between the heater and the sensing elements, more overshoot and undershoot can occur, causing a greater spread between maximum and minimum temperature. This spread can be reduced by selecting a PID controller.

CONTROL ALGORITHM (MODE)

This refers to the method in which the controller attempts to restore system temperature to the desired level. The two most common methods are two-position (on-off) and proportioning (throttling) controls.

ON/OFF CONTROL

On/Off control has the simplest of control modes. It has a deadband (differential) expressed as a percentage of the input span. The setpoint is usually in the center of the deadband. Therefore, if the input is 0-1000°F, the deadband is 5% and the setpoint is set at 500°F, the output will be full on when the temperature is 495°F or below and will stay full on until the temperature reaches 505°F, at which time the output will be full off. It will stay full off until the temperature drops to 495°F.

If the process has a fast rate of response, the cycling between 495 and 505°F will be fast. The faster the rate of response of the process, the greater the overshoot and undershoot and the faster the cycling of the contactor when used as a final control element.

On-off control is usually used where a precise control is not necessary, for example, in systems which cannot handle having the energy turned on and off frequently, where the mass of the system is so great that the temperature changes extremely slowly, or for a temperature alarm.

One special type of on-off control used for alarm is a limit controller. This controller uses a latching relay, which must be manually reset, and is used to shut down a process when a certain temperature is reached.

PROPORTIONAL

Proportional controls are designed to eliminate the cycling associated with on-off control. A proportional controller decreases the average power being supplied to the heater as the temperature approaches setpoint. This has the effect of slowing down the heater so that it will not overshoot the setpoint, but will approach the setpoint and maintain a stable temperature. This proportioning action can be accomplished by turning the output on and off for short intervals. This “time proportioning” varies the ratio of “on” time to “off ” time to control the temperature.

The time period between two successive turn-ons is known as the “cycle time” or “duty cycle”. The proportioning action occurs within a “proportional band” around the setpoint temperature. Outside this band, the controller functions as an on-off unit, with the output either fully on (below the band) or fully off (above the band). However, within the band, the output is turned on and off in the ratio of the measurement difference from the setpoint. At the setpoint (the midpoint of the proportional band), the output on-off ratio is 1:1 that is, the on-time and off-time are equal. If the temperature is further from the setpoint, the on- and off-times vary in proportion to the temperature difference. If the temperature is below setpoint, the output will be on longer. If the temperature is too high, the output will be off longer.

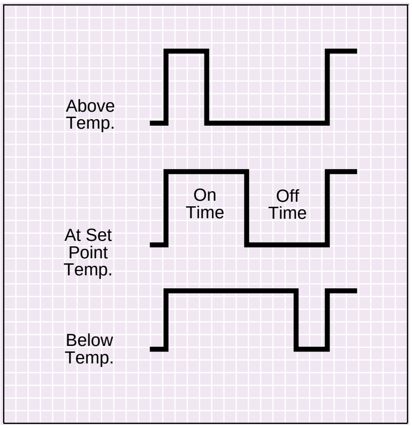


Figure 1: Proportional control

The proportional band is usually expressed as a percentage of full input range scale, or in degrees. It may also be referred to as gain, which is the reciprocal of the band. In many units, the cycle time and/or proportional bandwidth are adjustable, so that the controller may be better matched to a particular process.

Proportional controllers have a manual reset (trim) adjustment, which may be used to adjust for an offset between the steady state temperature and the setpoint.

In addition to electromechanical and solid state relay outputs, proportional controllers are also available with proportional analog signal outputs, such as 4 to 20 mA or 0 to 5 Vdc. With these outputs, the actual output level amplitude is varied, rather than the proportion of on and off times.

PROPORTIONAL PLUS INTEGRAL PLUS DERIVATIVE CONTROL MODE (PID):

This controller operates the same way a proportional controller does, except that the function of the trim adjustment is performed automatically by the integral function (automatic reset). Thus, load changes are compensated for automatically and the temperature agrees with the setpoint under all operating conditions. Offset is eliminated.

Temperature Controllers
Selection Considerations

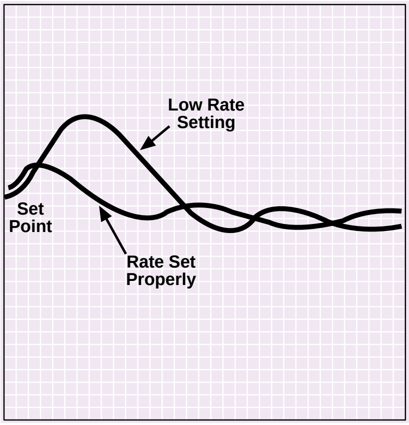


Figure 2: Rate function compensates for rapid changes.

The derivative function (rate action) compensates for load changes which take place rapidly. An example is a traveling belt oven where the product is fed intermittently. When the product enters the oven, there is a sharp rise in the demand for heat, and when it stops, there is an excess of heat. Derivative action reduces the undershoot and overshoot of temperature under these conditions and prevents bad product due to over or under curing.

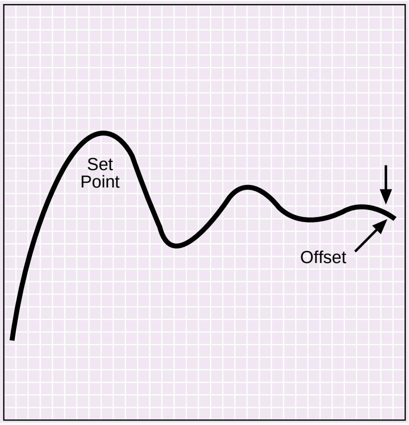


Figure 3: Reset fuction eliminates offset.

PID control provides more accurate and stable control than on/off or proportional controller types. It is best used in systems that have a relatively small mass and which react quickly to changes in energy added to the process. It is recommended in systems where the load changes often. The controller is expected to automatically compensate the amount of energy available or the mass to be controlled, due to frequent changes in setpoint.

The proportional, integral and derivative terms must be "tuned," *i.e.*, adjusted to a particular process. This is done by trial and error. Some controllers called Autotune controllers attempt to adjust the PID parameters automatically.

TYPE OF CONTROL OUTPUT HARDWARE

The output hardware in a temperature controller may take one of several forms. Deciding on the type of control hardware to be used depends on the heater used and power available, the control algorithm chosen, and the hardware external to the controller available to handle the heater load. The most commonly used controller output hardware is as follows:

Time Proportional or On/Off
  1) Mechanical Relay
  2) Triac (ac solid state relay)
  3) dc Solid State Relay Driver (pulse)

Analog Proportional
  1) 4-20 mA dc
  2) 0-5 Vdc or 0-10 Vdc

A time proportional output applies power to the load for a percentage of a fixed cycle time. For example, with a 10 second cycle time, if the controller output were set for 60%, the relay would be energized (closed, power applied) for 6 seconds, and de-energized (open, no power applied) for 4 seconds.

The electromechanical relay is generally the most economical output type, and is usually chosen on systems with cycle times greater than 10 seconds and relatively small loads.

Choose an ac solid state relay or dc voltage pulse to drive an external SSR with reliability, since they contain no moving parts. They are also recommended for processes requiring short cycle times. External solid state relays may require an ac or dc control signal.

An amplitude proportional output is usually an analog voltage (0 to 5 Vdc) or current (4 to 20 mA). The output level from this output type is also set by the controller. If the output were set at 60%, the output level would be 60% of 5 V, or 3 V. With a 4 to 20 mA output (a 16 mA span), 60% is equal to (0.6 x 16) + 4, or 13.6 mA. These controllers are usually used with SCR power controllers or proportioning valves.

The power used by an electrical resistance heater will usually be given in watts. The capacity of a relay is given in amps. A common formula to determine the safe relay rating requirements is:

$W = V(A)(1.5)$ or $A = W/(V)(1.5)$
Where A = relay rating in amps
W = heater capacity in watts
V = voltage used
1.5 = safety factor

The types of hardware available, external to the controller, to allow it to handle the load, are as follows:

1) Mechanical Contactor
2) ac controlled solid state relay
3) dc controlled solid state relay
4) Zero crossover SCR power controller
5) Phase angle fired SCR power controller

Mechanical contactors are external relays, which can be used when a higher amperage than can be handled by the relay in the controller is required, or for some three-phase systems. They are not recommended for cycle times shorter than 15 seconds.

Solid state relays have the advantage over mechanical contactors, in that they have no moving parts, and thus can be used with short cycle times. The shorter the cycle time, the less dead lag and the better the control. The "switching" takes place at the zero voltage crossover point of the alternating current cycle; thus, no appreciable electrical noise is generated. An ac controlled solid state relay is used with either a mechanical relay or triac output from the controller, and is available for currents up to 90 amps at voltages of up to 480 Vac. DC solid state relays are used with dc solid state driver (pulse) outputs. The "turn on" signal can be from 3 to 32 Vdc and models are available to control up to 90 amps at up to 480 Vac.

Zero crossover SCR power controllers are used to control single or three-phase power for even larger loads. They can be used for currents up to 200 amps at 480 volts. A 4-20 mA dc control signal is usually required from the controller. The zero crossover SCR power controllers convert the analog output signal to a time proportional signal with a cycle time of about two seconds or less, and also provide switching at the zero crossover point to avoid generating electrical noise.

Phase angle SCR power controllers also are operated by a 4-20 mA dc controller output. Power to the load is controlled by governing the point of turn on (firing) of each half cycle of a full ac sine wave. This has the effect of varying the voltage within a single 0.0167 second period. By comparison, time proportional controllers vary the average power over the cycle time, usually more than 1 second, and often more than 15 seconds. Phase angle SCR's are only recommended for low mass heating elements such as infrared lamps or hot wire heaters.

Temperature Control
Tuning a PID (Three Mode) Controller

Tuning a temperature controller involves setting the proportional, integral, and derivative values to get the best possible control for a particular process. If the controller does not include an autotune algorithm, or if the autotune algorithm does not provide adequate control for the particular application, then the unit must be tuned using trial and error.

The following is a tuning procedure for the OMEGA CN2000 controller. It can be applied to other controllers as well. There are other tuning procedures which can also be used, but they all use a similar trial and error method. Note that if the controller uses a mechanical relay (rather than a solid state relay), a longer cycle time (20 seconds) should be used when starting out.

The following definitions may be needed:

1) Cycle time - Also known as duty cycle; the total length of time for the controller to complete one on/off cycle. Example: with a 20 second cycle time, an on time of 10 seconds and an off time of 10 seconds represents a 50 percent power output. The controller will cycle on and off while within the proportional band.
2) Proportional band - A temperature band expressed in % of full scale or degrees within which the controller‘s proportioning action takes place. The wider the proportional band, the greater the area around the setpoint in which the proportional action takes place. This is sometimes referred to as gain, which is the reciprocal of proportional band.
3) Integral, also known as reset, is a function which adjusts the proportional bandwidth with respect to the setpoint to compensate for offset (droop) from setpoint; that is, it adjusts the controlled temperature to setpoint after the system stabilizes.
4) Derivative, also known as rate, senses the rate of rise or fall of system temperature and automatically adjusts the proportional band to minimize overshoot or undershoot.

A PID (three mode) controller is capable of exceptional control stability when properly tuned and used. The operator can achieve the fastest response time and smallest overshoot by following these instructions carefully. The information for tuning this three mode controller may be different from other controller tuning procedures. Normally a SELF TUNE feature will eliminate the need to use this manual tuning procedure for the primary output; however, adjustments to the SELF TUNE values may be made if desired.

After the controller is installed and wired:

1. Apply power to the controller.
2. Disable the control outputs if possible.
3. For time proportional primary output, set the cycle time. Enter the following value:

CYCLE TIME 1

5 SEC (Only appears if output is a time proportional output. A smaller cycle time may be required for systems with an extremely fast response time.)

Then select the following parameters:

PR BAND 1 _______5% (PB)

RESET 1 _________0 R/M (TURNS OFF RESET FUNCTION)

RESET 2 _________0 R/M

RATE 1 __________0 MIN (TURNS OFF RATE FUNCTION)

RATE 2 __________0 MIN

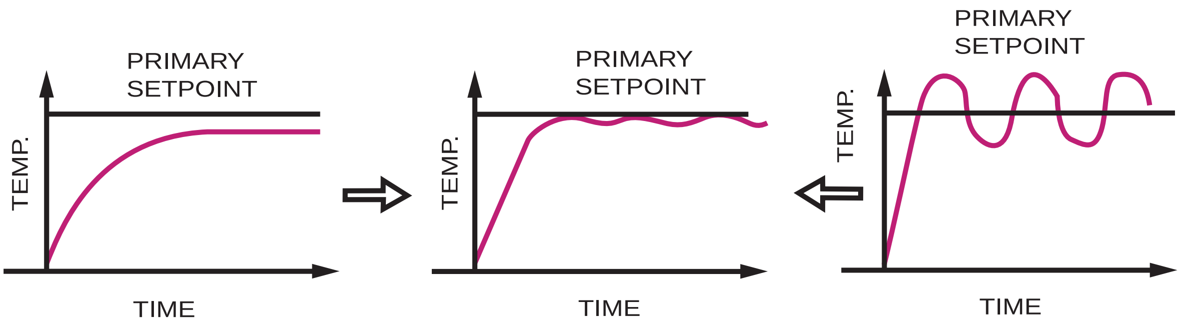
NOTE

On units with dual three mode outputs, the primary and secondary tuning parameters are independently set and must be tuned separately. The procedure used in this section is for a HEATING primary output. A similar procedure may be used for a primary COOLING output or a secondary COOLING output.

A. TUNING OUTPUTS FOR HEATING CONTROL

1. Enable the OUTPUT(S) and start the process.
2. The process should be run at a setpoint that will allow the temperature to stabilize with heat input required.
3. With RATE and RESET turned OFF, the temperature will stabilize with a steady state deviation, or droop, between the setpoint and the actual temperature. Carefully note whether or not there are regular cycles or oscillations in this temperature by observing the measurement on the display. (An oscillation may be as long as 30 minutes.)

   The tuning procedure is easier to follow if you use a recorder to monitor the process temperature.



Divide PB by 2 if you observe this.

This is close to perfect tuning.

Multiply PB by 2 if you observe this.

Figure 1. Temperature Oscillations

4. If there are no regular oscillations in the temperature, divide the PB by 2 (see Figure 1). Allow the process to stabilize and check for temperature oscillations. If there are still no oscillations, divide the PB by 2 again. Repeat until cycles or oscillations are obtained. Proceed to Step 5.

   If oscillations are observed immediately, multiply the PB by 2. Observe the resulting temperature for several minutes. If the oscillations continue, increase the PB by factors of 2 until the oscillations stop.

5. The PB is now very near its critical setting. Carefully increase or decrease the PB setting until cycles or oscillations just appear in the temperature recording.

   If no oscillations occur in the process temperature even at the minimum PB setting of 1%, skip Steps 6 through 11 below and proceed to paragraph B.

6. Read the steady-state deviation, or droop, between setpoint and actual temperature with the “critical” PB setting you have achieved. (Because the temperature is cycling a bit, use the average temperature.)

7 Measure the oscillation time, in minutes, between neighboring peaks or valleys (see Figure 2). This is most easily accomplished with a chart recorder, but a measurement can be read at one minute intervals to obtain the timing.

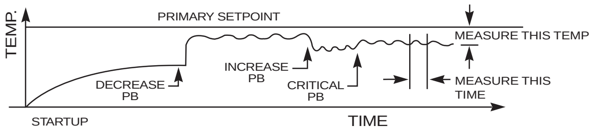


Figure 2. Oscillation Time

8. Now, increase the PB setting until the temperature deviation, or droop, increases 65%.

   The desired final temperature deviation can be calculated by multiplying the initial temperature deviation achieved with the CRITICAL PB setting by 1.65 (see Figure 3) or by use of the convenient Nomogram I (see Figure 4). Try several trial-and-error settings of the PB control until the desired final temperature deviation is achieved.

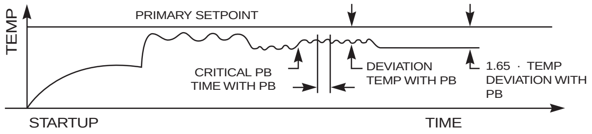


Figure 3. Calculating Final Temperature Deviation

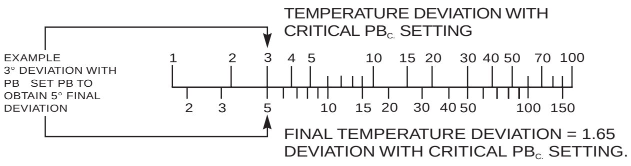


Figure 4. Nomogram I

9. You have now completed all the measurements necessary to obtain optimum performance from the Controller. Only two more adjustments are required - RATE and RESET.

10. Using the oscillation time measured in Step 7, calculate the value for RESET in repeats per minutes as follows:

    $$\text{RESET} = \frac{8}{5} \times \frac{1}{T_O}$$

    Where T_O = Oscillation Time in Minutes.
    OR Use Nomogram II (see Figure 5):

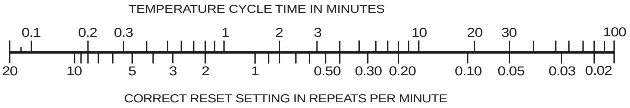


Figure 5. Nomogram II

    Enter the value for RESET 1.

11. Again using the oscillation time measured in Step 7, calculate the value for RATE in minutes as follows:

    $$\text{RESET} = \frac{T_O}{10}$$

    Where T_O = Oscillation Time
    OR Use Nomogram III (see Figure 6)

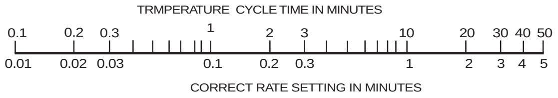


Figure 6. Nomogram III

    Enter this value for Rate 1.

12. If overshoot occurred, it can be eliminated by decreasing the RESET time. When changes are made in the RESET value, a corresponding change should also be made in the RATE adjustment so that the RATE value is equal to:

    $$\text{RATE} = \frac{1}{6 \text{ x Reset Value}}$$

    _i.e._, if reset = 2 R/M, the
    RATE = 0.08 min.

13. Several setpoint changes and consequent RESET and RATE time adjustments may be required to obtain the proper balance between “RESPONSE TIME” to a system upset and “SETTLING TIME.” In general, fast response is accompanied by larger overshoot and consequently shorter time for the process to “SETTLE OUT.” Conversely, if the response is slower, the process tends to slide into the final value with little or no overshoot. The requirements of the system dictate which action is desired.

14. When satisfactory tuning has been achieved, the cycle time should be increased to save contactor life (applies to units with time proportioning outputs only (TPRI)). Increase the cycle time as much as possible without causing oscillations in the measurement due to load cycling.

15. Proceed to Section C.

Tuning a PID Controller Cont'd

B. TUNING PROCEDURE WHEN NO OSCILLATIONS ARE OBSERVED

1. Measure the steady-state deviation, or droop, between setpoint and actual temperature with minimum PB setting.
2. Increase the PB setting until the temperature deviation (droop) increases 65%. Nomogram I (see Figure 4) provides a convenient method of calculating the desired final temperature deviation.
3. Set the RESET 1 to a high value (10 R/M). Set the RATE 1 to a corresponding value (0.02 MIN). At this point, the measurement should stabilize at the setpoint temperature due to reset action.
4. Since we were not able to determine a critical oscillation time, the optimum settings of the reset and rate adjustments must be determined by trial and error. After the temperature has stabilized at setpoint, increase the setpoint temperature setting by 10 degrees. Observe the overshoot associated with the rise in actual temperature. Then return the setpoint setting to its original value and again observe the overshoot associated with the actual temperature change.

   Excessive overshoot implies that the RESET and/or RATE values are set too high. Overdamped response (no overshoot) implies that the RESET and/or RATE values are set too low. Refer to Figure 7. Where improved performance is required, change one tuning parameter at a time and observe its effect on performance when the setpoint is changed. Make incremental changes in the parameters until the performance is optimized.
5. When satisfactory tuning has been achieved, the cycle time should be increased to save contactor life (applies to units with time proportioning outputs only (TPRI)). Increase the cycle time as much as possible without causing oscillations in the measurement due to load cycling.

RESET OR RATE TOO HIGH RESET OR RATE TOO LOW

Figure 7. Setting RESET and/or RATE

C. TUNING THE PRIMARY OUTPUT FOR COOLING CONTROL

The same procedure is used as for heating. The process should be run at a setpoint that requires cooling control before the temperature will stabilize.

D. SIMPLIFIED TUNING PROCEDURE FOR PID CONTROLLERS

The following procedure is a graphical technique of analyzing a process response curve to a step input. It is much easier with a strip chart recorder reading the process variable (PV).

1. Starting from a cold start (PV at ambient), apply full power to the process without the controller in the loop, *i.e.*, with an open loop. Record this starting time.
2. After some delay (for heat to reach the sensor), the PV will start to rise. After more delay, the PV will reach a maximum rate of change (slope). Record the time at which this maximum slope occurs and the PV at which it occurs. Record the maximum slope in degrees per minute. Turn off system power.
3. Draw a line from the point of maximum slope back to the ambient temperature axis to obtain the lumped system time delay Td (see Figure 8). The time delay may also be obtained by the equation:

   Td = time to max. slope-(PV at max. slope - Ambient)/max. slope
4. Apply the following equations to yield the PID parameters:

   Pr. Band = Td x max. slope x 100/span = % of span
   Reset= 0.4 / Td = resets/minute
   Rate = 0.4 x Td = minutes
5. Restart the system and bring the process to setpoint with the controller in the loop and observe response. If the response has too much overshoot, or is oscillating, then the PID parameters can be changed (slightly, one at a time, and observing process response) in the following directions:

   Widen the proportional band, lower the Reset value, and increase the Rate value.

Example: The chart recording in Figure 8 was obtained by applying full power to an oven. The chart scales are 10°F/cm, and 5 min/cm. The controller range is 100 to 600°F, or a span of 500°F.

Maximum slope = 18°F/5 minutes
= 3.6°F/minute

Time delay = Td = approximately 7 minutes.

Proportional Band = 7 minutes x 3.6°F/minutes x 100/500°F = 5%.

Reset = 0.4/7 minutes = 0.06 resets/minute

Rate = 0.4 x 7 minutes = 2.8 minute

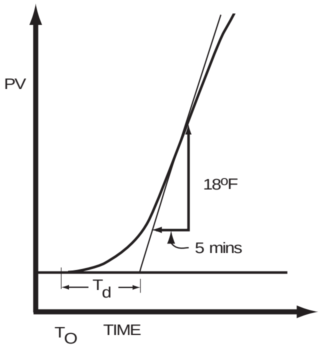


Figure 8. System Time Delay

Controller Operation

There are three basic types of controllers: on-off, proportional and PID. Depending upon the system to be controlled, the operator will be able to use one type or the other to control the process.

On/Off

An on-off controller is the simplest form of temperature control device. The output from the device is either on or off, with no middle state. An on-off controller will switch the output only when the temperature crosses the setpoint. For heating control, the output is on when the temperature is below the setpoint, and off above setpoint.

Since the temperature crosses the setpoint to change the output state, the process temperature will be cycling continually, going from below setpoint to above, and back below. In cases where this cycling occurs rapidly, and to prevent damage to contactors and valves, an on-off differential, or "hysteresis," is added to the controller operations. This differential requires that the temperature exceed setpoint by a certain amount before the output will turn off or on again. On-off differential prevents the output from "chattering" or making fast, continual switches if the cycling above and below the setpoint occurs very rapidly.

On-off control is usually used where a precise control is not necessary, in systems which cannot handle having the energy turned on and off frequently, where the mass of the system is so great that temperatures change extremely slowly, or for a temperature alarm.

One special type of on-off control used for alarm is a limit controller. This controller uses a latching relay, which must be manually reset, and is used to shut down a process when a certain temperature is reached.

Proportional

Proportional controls are designed to eliminate the cycling associated with on-off control. A proportional controller decreases the average power supplied to the heater as the temperature approaches setpoint. This has the effect of slowing down the heater so that it will not overshoot the setpoint, but will approach the setpoint and maintain a stable temperature. This proportioning action can be accomplished by turning the output on and off for short intervals. This "time proportioning" varies the ratio of "on" time to "off" time to control the temperature. The proportioning action occurs within a "proportional band" around the setpoint temperature. Outside this band, the controller functions as an on-off unit, with the output either fully on (below the band) or fully off (above the band). However, within the band, the output is turned on and off in the ratio of the measurement difference from the setpoint. At the setpoint (the midpoint of the proportional band), the output on:off ratio is 1:1; that is, the on-time and off-time are equal. if the temperature is further from the setpoint, the on- and off-times vary in proportion to the temperature difference. If the temperature is below setpoint, the output will be on longer; if the temperature is too high, the output will be off longer.

The proportional band is usually expressed as a percentage of full scale, or degrees. It may also be referred to as gain, which is the reciprocal of the band. Note that in time proportioning control, full power is applied to the heater, but cycled on and off, so the average time is varied. In most units, the cycle time and/or proportional band are adjustable, so that the controller may better match a particular process.

In addition to electromechanical and solid state relay outputs, proportional controllers are also available with proportional analog outputs, such as 4 to 20 mA or 0 to 5 Vdc. With these outputs, the actual output level is varied, rather than the on and off times, as with a relay output controller.

One of the advantages of proportional control is the simplicity of operation. It may require an operator to make a small adjustment (manual reset) to bring the temperature to setpoint on initial startup, or if the process conditions change significantly.

Systems that are subject to wide temperature cycling will also need proportional controllers. Depending upon the process and the precision required, either a simple proportional control or one with PID may be required.

Processes with long time lags and large maximum rates of rise (*e.g.*, a heat exchanger), require wide proportional bands to eliminate oscillation. The wide band can result in large offsets with changes in the load. To eliminate these offsets, automatic reset (integral) can be used. Derivative (rate) action can be used on processes with long time delays, to speed recovery after a process disturbance.

PID

The third controller type provides proportional with integral and derivative control, or PID. This controller combines proportional control with two additional adjustments, which helps the unit automatically compensate for changes in the system. These adjustments, integral and derivative, are expressed in time-based units; they are also referred to by their reciprocals, RESET and RATE, respectively.

The proportional, integral and derivative terms must be individually adjusted or "tuned" to a particular system using trial and error. It provides the most accurate and stable control of the three controller types, and is best used in systems which have a relatively small mass, those which react quickly to changes in the energy added to the process. It is recommended in systems where the load changes often and the controller is expected to compensate automatically due to frequent changes in setpoint, the amount of energy available, or the mass to be controlled.

There are also other features to consider when selecting a controller. These include auto- or self-tuning, where the instrument will automatically calculate the proper proportional band, rate and reset values for precise control; serial communications, where the unit can "talk" to a host computer for data storage, analysis, and tuning; alarms, that can be latching (manual reset) or non-latching (automatic reset), set to trigger on high or low process temperatures or if a deviation from setpoint is observed; timers/event indicators which can mark elapsed time or the end/beginning of an event. In addition, relay or triac output units can be used with external switches, such as SSR solid state relays or magnetic contactors, in order to switch large loads up to 75 A.

Solid State Relays

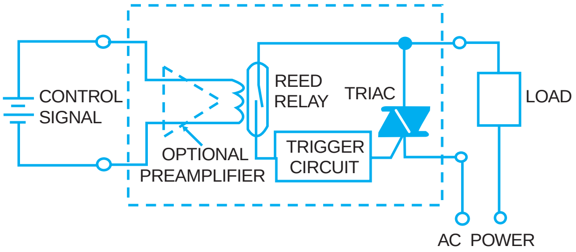


Figure 1. Hybrid SSR

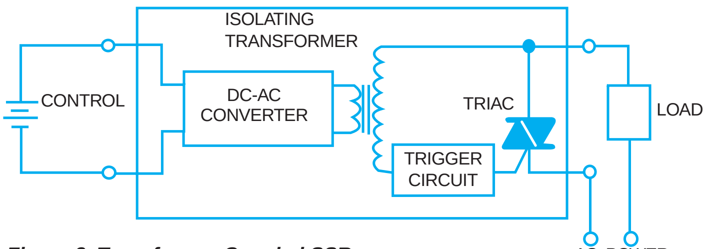


Figure 2. Transformer-Coupled SSR

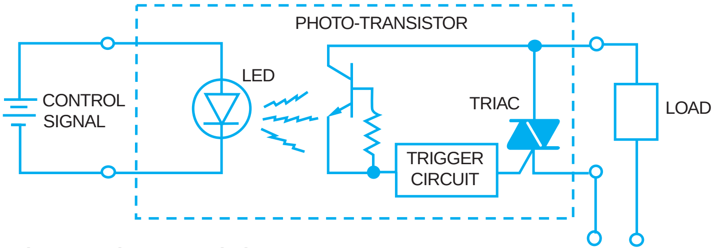


Figure 3. Photo-Coupled SSR

Defined and Described

SSR Defined. A solid-state relay is an ON-OFF control device in which the load current is conducted by one or more *semiconductors* - e.g., a power transistor, an SCR, or a TRIAC. (The SCR and TRIAC are often called “thyristors,” a term derived by combining *thyratron* and *transistor*, since thyristors are *triggered semiconductor switches.*)

Like all relays, the SSR requires relatively low control-circuit energy to switch the output state from OFF to ON, or vice versa. Since this control energy is very much lower than the output power controllable by the relay at full load, "power gain" in an SSR is substantial--frequently much higher than in an electromagnetic relay of comparable output rating. To put it another way, the *sensitivity* of an SSR is often significantly higher than that of an EMR of comparable output rating.

Types of SSR's. It is convenient to classify SSR's *by the nature of the input circuit*, with particular reference to the means by which input-output isolation is achieved. Three major categories are recognized:

- **Reed-Relay-Coupled SSR's** (see figure 1), in which the control signal is applied (directly, or through a preamplifier) to the coil of a reed relay. The closure of the reed switch then activates appropriate circuitry that triggers the thyristor switch. Clearly, the input-output isolation achieved is that of the reed relay, which is usually excellent.
- **Transformer-Coupled SSR's** (see figure 2), in which the control signal is applied (through a DC-AC converter, if it is DC, or directly, if It is AC) to the primary of a small, low-power transformer, and the secondary voltage that results from the primary excitation is used (with or without rectification, amplification, or other modification) to trigger the thyristor switch. In this type, the degree of input-output isolation depends on the design of the transformer.
- **Photo-coupled SSR's** (see figure 3), in which the control signal is applied to a light or infrared source (usually, a light-emitting diode, or LED), and the radiation from that source is detected in a photo-sensitive semi-conductor (i.e., a photosensitive diode, a photo-sensitive transistor, or a photo-sensitive thyristor). The output of the photo-sensitive device is then used to trigger (gate) the TRIAC or the SCR's that switch the load current. Clearly, the only significant “coupling path” between input and output is the beam of light or infra-red radiation, and electrical isolation is excellent. These SSR's are also referred to as *“optically coupled”* or *“photo-isolated”*.

In addition to the major types of SSR's described above, there are some special-purpose designs that should be mentioned:

- Direct-control AC types (see figure 4), in which external contacts, operating in a circuit energized by the same AC power line as is used for the load circuit, trigger a TRIAC (or back-to-back-connected SCR's). This type is also referred to as having a “switch closure” input. Clearly, this type of relay, while simpler and inherently less expensive than more sophisticated designs, has the great disadvantage (for most applications) of having no isolation between the control and load circuits.
- Direct-control DC types (see figure 5) in which external contacts, operating in a circuit energized by the same DC power line as is used for the load circuit, control the conduction of a transistor. This type of relay, which is perhaps the simplest of all, and inherently the least expensive, also has the great disadvantage (for most applications) of having no isolation between the control and load circuits.
- SCR types designed for DC, in which the load-current-carrying SCR is made to turn off by means of a second

Solid State Relays Cont'd

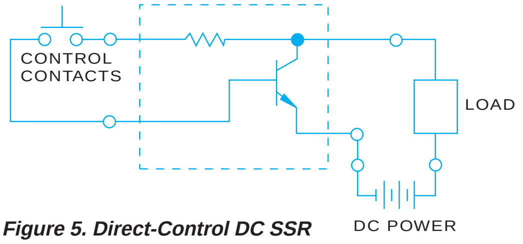


Figure 5. Direct-Control DC SSR

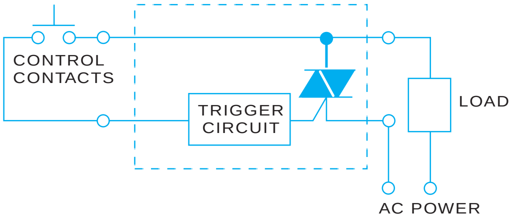


Figure 4. Direct-Control AC SSR

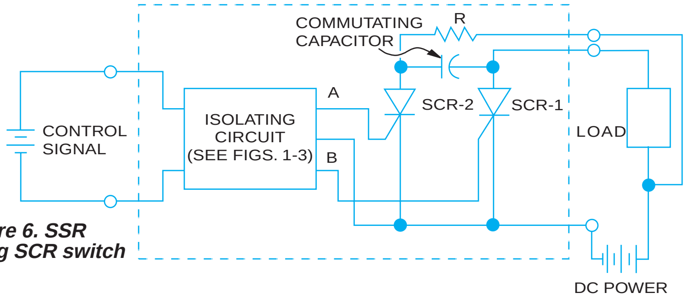


Figure 6. SSR using SCR switch

SCR, connected in a "commutating circuit" (such as that of figure 6), which is capable of turning off the first SCR by momentarily reducing its current to zero.

- Designs using special isolating means, such as. . .

  ...the Hall effect in which the motion of a magnet external to, but in proximity to, the SSR causes a change in resistance in a field -sensitive material, thereby triggering on-off behavior.

  ...oscillator tuning, in which the external signal shifts the frequency of an oscillator, thereby causing a closely coupled resonant circuit to trigger on-off behavior.

  ...saturable reactors or magnetic amplifiers, in which a DC control current in one winding controls the induced voltage (from an AC source) in another winding. The induced voltage is then used to trigger on-off behavior.

It is safe to say that well over 95% of all SSR requirements are best satisfied by one of the three major types described earlier (***i.e.***, figures 1-3).

Input Circuit Performance. The sensitivity of **isolated** SSR's (that is, the minimum control voltage and current at which the SSR turns on) depends on the characteristics of the isolating component or circuit:

- In hybrid (reed-relay isolated) designs, the SSR's sensitivity is established by the operating-power requirement of the reed relay, which ranges from as low as 40 milliwatts (e.g., 5 volts dc at 8 mA) to as high as several hundred milliwatts. Note that the low-voltage, low-power designs are compatible with standard digital-computer "logic levels," and that the standard "high-fan-out" TTL logic-level output from a digital computer or digital controller can drive two or more hybrid SSR's in parallel.
- In transformer-coupled SSR's, the sensitivity is usually considerably higher than that of the hybrid type, because all the input signal must do is to gate on the AC-DC converter (see figure 2) that drives the transformer, and that requires, typically, less than 10 milliwatts (e.g., 4.5 v dc at 2 mA) and rarely more than 50 milliwatts. This sensitivity is better than required by any single-TTL digital output, and a high-fan-out TTL output can drive from 3 to 10 such SSR's in parallel.
- In optically coupled SSR's, the sensitivity ranges from about 6 milliwatts (e.g., 3 volts dc at 2 mA) to 100 milliwatts. Using an appropriate series resistor or current regulator, this type of input circuit is also compatible with TTL logic levels, and several optically coupled SSR's can be driven in parallel by high-fan-out logic lines.
- The sensitivity of most "direct-control" SSR's (figures 4 and 5) is significantly lower than that of the isolated designs, but that fact is of little importance because the control power required is almost always well within the capability of even the smallest control contacts.

The *maximum* turn-off level (voltage and/or current) of an SSR is about 50% of the *minimum* level at which it turns on. This characteristic provides an adequate margin of safety between the ON and OFF states, thereby eliminating erratic behavior due to small changes in the control signal.

In many SSR designs, the control-voltage *range* is much greater than that implied by the minimum turn-on voltage. In designs optimized for wide input voltage range, it is not uncommon for the SSR to be rated for use over more than a 6-to-1 range of control voltages (e.g., 3.0 V to 32 V). In hybrid designs, the coil of the reed relay may be wound for almost any useful control voltage, from as low as 3 volts nominal, to 50 volts, or even higher, but the *range* of input voltage tolerated by a hybrid SSR is limited by dissipation in the relay coil. Generally, a range of 1.5 to 1 is acceptable. On the other hand, series resistance, or a "constant-current" active input circuit, may be used to accommodate a hybrid relay to higher input voltages.

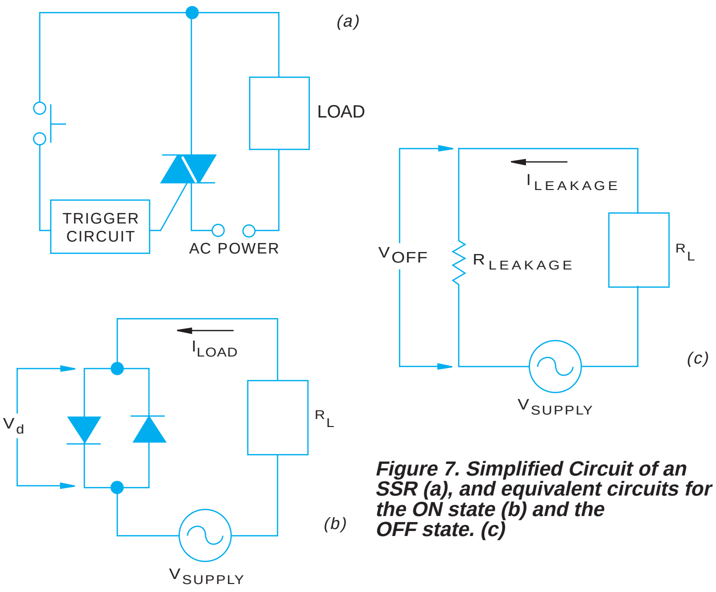


Figure 7. Simplified Circuit of an SSR (a), and equivalent circuits for the ON state (b) and the OFF state. (c)

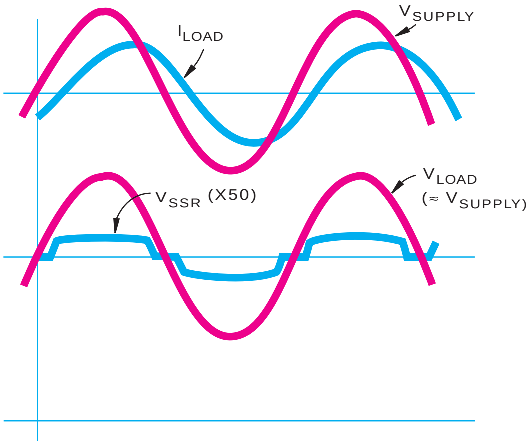


Figure 8a. ON-Mode Waveforms** **(V_{SSR} is greatly exaggerated)

Input Characteristics. Beyond consideration of the sensitivity characteristics (page Z-120), we must also describe the input-circuit *isolation* characteristics of an SSR, which requires consideration of many different parameters, including:

- **Dielectric strength,** rated in terms of minimum breakdown voltage from control circuit to both the SSR case and the output (load) circuit. A typical rating is 1500 volts ac (RMS), for either control to case or control to output.
- **Insulation Resistance,** from control circuit to both the case and the output circuit. Typical ratings range from 10 megohms to 100,000 megohms for transformer and hybrid designs. For optically isolated SSR's, typical insulation resistances range from 1000 to 1 million megohms.
- **Stray Capacitance** from control circuit to both case and the output circuit. Capacitance to case is rarely significant, but capacitance to the output circuit may couple ac and transients back to the sensitive control circuit, and even further back, into the control-signal sources. Fortunately, in well designed SSR's, this capacitance is rarely large enough to cause interaction. Typical stray capacitance ranges from 1 to 10 picofarads.

The speed of response of the SSR to the application of control voltage is covered later in this section.

Output Circuit Performance. Clearly, the most significant output-circuit parameters are the maximum load-circuit voltage that may be impressed across the relay output circuit in the OFF condition without causing it to break down into conduction or failure, and the maximum current that can flow through the output circuit and load in ON condition.

Note that these parameters are (at least at first glance) analogous to the usual voltage and current ratings of the contacts on an electro-magnetic relay. There are, however, differences between EMR output ratings and SSR output ratings--differences that will be examined in detail as this exposition proceeds.

In the most general approach, one may say that the "contact ratings" of an SSR are determined almost entirely by the characteristics of the load-current switching device. Perhaps this fact is most apparent from an examination of the simplest type of ac SSR - a direct-control (non-isolated) design, such as that originally shown in figure 4, and redrawn above in figure 7, with its equivalent circuit for both the ON and OFF states. In the ON state (figure 7b), the TRIAC exhibits a nearly constant voltage drop (<u>*i.e.*</u>, almost independent of load current) approximately equal to that of two silicon diodes - less than 2 volts. The passage of load current through this voltage drop causes power dissipation (P_d = V_d x I_{load}), and this power will cause a temperature rise in the TRIAC junction. If proper "heat-sinking" is provided - <u>*i.e.*</u>, thermal conduction from the TRIAC case to the outside air or to a heat-conductive metal structure that can in turn dissipate the power to the surrounding air without significant temperature rise - then the TRIAC temperature will not rise above the rated maximum value for reliable operation (typically, 100°C). With *generous* heat sinking, the current rating of the SSR may be determined, not by power dissipation, but by the current rating of the TRIAC.

Figure 7c shows the equivalent circuit of this very simple SSR in the OFF state. Note that even when the TRIAC is turned off, a very small amount of leakage current can flow. This current path, represented by a resistance in the equivalent circuit, is actually a non-linear function of the load-circuit voltage. The normal practice, in rating