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Features and Applications of RCA Integrated-Circuit Zero-Voltage Switches (CA3058, CA3059, and CA3079)

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RCA-CA3058, CA3059 and CA3079 zero-voltage switches are monolithic integrated circuits designed primarily for use as trigger circuits for thyristors in many highly diverse ac power-control and power-switching applications. These integrated-circuit switches operate from an ac input voltage of 24, 120, 208 to 230, or 277 volts at 50, 60, or 400 Hz.

The CA3059 and CA3079 are supplied in a 14-terminal dual-in-line plastic package. The CA3058 is supplied in a 14-terminal dual-in-line ceramic package. The electrical and physical characteristics of each type are detailed in RCA Data Bulletin File No. 490.

RCA zero-voltage switches (ZVS) are particularly well suited for use as thyristor trigger circuits. These switches trigger the thyristors at zero-voltage points in the supply-voltage cycle. Consequently, transient load-current surges and radio-frequency interference (RFI) are substantially reduced. In addition, use of the zero-voltage switches also reduces the rate of change of on-state current (di/dt) in the thyristor being triggered, an important consideration in the operation of thyristors. These switches can be adapted for use in a variety of control functions by use of an internal differential comparator to detect the difference between two externally developed voltages. In addition, the availability of numerous terminal connections to internal circuit points greatly increases circuit flexibility and further expands the types of ac power-control applications to which these integrated circuits may be adapted. The excellent versatility of the zero-voltage switches is demonstrated by the fact that these circuits have been used to provide transient-free temperature control in self-cleaning ovens, to control gun-muzzle temperature in low-temperature environments, to provide sequential switching of heating elements in warm-air furnaces, to switch traffic signal lights at street intersections, and to effect other widely different ac power-control functions.

FUNCTIONAL DESCRIPTION

RCA zero-voltage switches are multistage circuits that employ a diode limiter, a zero-crossing (threshold) detector, an on-off sensing amplifier (differential comparator), and a Darlington output driver (thyristor gating circuit) to provide the basic switching action. The dc operating voltages for these stages is provided by an internal power supply that has sufficient current capability to drive external circuit elements, such as transistors and other integrated circuits. An important feature of the zero-voltage switches is that the output trigger pulses can be applied directly to the gate of a triac or a silicon controlled rectifier (SCR). The CA3058 and CA3059 also feature an interlock (protection) circuit that inhibits the application of these pulses to the thyristor in the event that the external sensor should be inadvertently opened or shorted. An external inhibit connection (terminal No. 1) is also available so that an external signal can be used to inhibit the output drive. This feature is not included in the CA3079; otherwise, the three integrated-circuit zero-voltage switches are electrically identical.

Over-all Circuit Operation

Fig. 1 shows the functional interrelation of the zero-voltage switch, the external sensor, the thyristor being triggered, and the load elements in an on-off type of ac power-control system. As shown, each of the zero-voltage switches incorporates four functional blocks as follows:

(1) Limiter-Power Supply – Permits operation directly from an ac line.

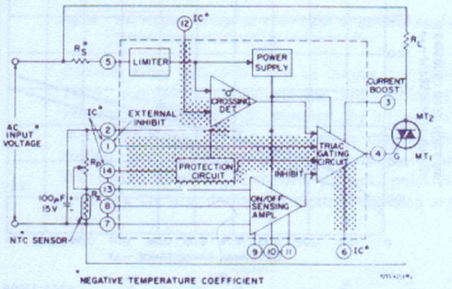
(2) Differential On/Off Sensing Amplifier – Tests the condition of external sensors or command signals. Hysteresis or proportional-control capability may easily be implemented in this section.

(3) Zero-Crossing Detector – Synchronizes the output pulses of the circuit at the time when the ac cycle is at a zero-voltage point and thereby eliminates radio-frequency inteference (RFI) when used with resistive loads.

(4) Triac Gating Circuit – Provides high-current pulses to the gate of the power-controlling thyristor.

In addition, the CA3058 and CA3059 provide the following important auxiliary functions (shown in Fig. 1):

(1) A built-in protection circuit that may be actuated to remove drive from the triac if the sensor opens or shorts.



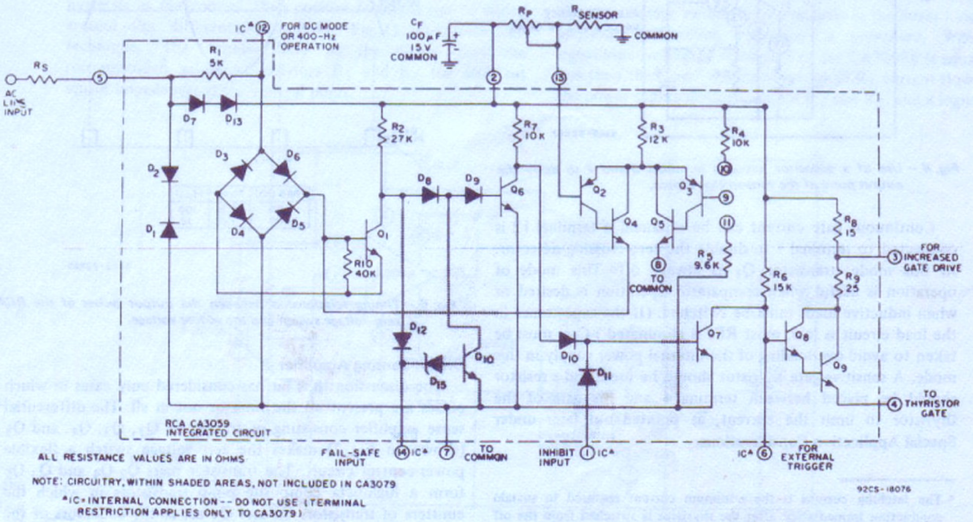
*NEGATIVE TEMPERATURE COEFFICIENT

AC Input Voltage (50/60 or 400 Hz) V AC	Input Series Resistor (R_S) k Ω	Dissipation Rating for R_S W
24	2	0.5
120	10	2
208/230	20	4
277	25	5

Fig. 1 – Functional block diagrams of the zero-voltage switches CA3058, CA3059, and CA3079.

(2) Thyristor firing may be inhibited through the action of an internal diode gate connected to terminal 1.

(3) High-power dc-comparator operation is provided by overriding the action of the zero-crossing detector. This override is accomplished by connecting terminal 12 to terminal 7. Gate current to the thyristor is continuous when terminal 13 is positive with respect to terminal 9.



ALL RESISTANCE VALUES ARE IN OHMS

NOTE: CIRCUITRY, WITHIN SHADED AREAS, NOT INCLUDED IN CA3079

*IC=INTERNAL CONNECTION -- DO NOT USE (TERMINAL RESTRICTION APPLIES ONLY TO CA3079)

Fig. 2 – Schematic diagram of zero-voltage switches CA3058, CA3059, and CA3079.

Fig. 2 shows the detailed circuit diagram for the integrated-circuit zero-voltage switches. (The diagrams shown in Figs. 1 and 2 are representative of all three RCA zero-voltage switches, i.e., the CA3058, CA3059, and CA3079; the shaded areas indicate the circuitry that is not included in the CA3079.)

The limiter stage of the zero-voltage switch clips the incoming ac line voltage to approximately ±8 volts. This signal is then applied to the zero-voltage-crossing detector, which generates an output pulse each time the line voltage passes through zero. The limiter output is also applied to a rectifying diode and an external capacitor, C_F, that comprise the dc power supply. The power supply provides approximately 6 volts as the V_{CC} supply to the other stages of the zero-voltage switch. The on-off sensing amplifier is basically a differential comparator. The thyristor gating circuit contains a driver for direct triac triggering. The gating circuit is enabled when all the inputs are at a "high" voltage, i.e., the line voltage must be approximately zero volts, the sensing-amplifier output must be "high," the external voltage to terminal 1 must be a logical "0", and, for the CA3058 and CA3059, the output of the fail-safe circuit must be "high." Under these conditions, the thyristor (triac or SCR) is triggered when the line voltage is essentially zero volts.

Thyristor Triggering Circuits

The diodes D_1 and D_2 in Fig. 2 form a symmetrical clamp that limits the voltages on the chip to ±8 volts; the diodes D_7 and D_{13} form a half-wave rectifier that develops a positive voltage on the external storage capacitor, C_F.

The output pulses used to trigger the power-switching thyristor are actually developed by the zero-crossing detector and the thyristor gating circuit. The zero-crossing detector consists of diodes D_3 through D_6, transistor Q_1, and the associated resistors shown in Fig. 2. Transistors Q_1 and Q_6 through Q_9 and the associated resistors comprise the thyristor gating circuit and output driver. These circuits generate the output pulses when the ac input is at a zero-voltage point so that RFI is virtually eliminated when the zero-voltage switch and thyristor are used with resistive loads.

The operation of the zero-crossing detector and thyristor gating circuit can be explained more easily if the on state (i.e., the operating state in which current is being delivered to the thyristor gate through terminal 4) is considered as the operating condition of the gating circuit. Other circuit elements in the zero-voltage switch inhibit the gating circuit unless certain conditions are met, as explained later.

In the on state of the thyristor gating circuit, transistors Q_8 and Q_9 are conducting, transistor Q_7 is off, and transistor Q_6 is on. Any action that turns on transistor Q_7 removes the drive from transistor Q_8 and thereby turns off the thyristor. Transistor Q_7 may be turned on directly by application of a minimum of ±1.2 volts at 10 microamperes to the external-inhibit input, terminal 1. (If a voltage of more than

1.5 volts is available, an external resistance must be added in series with terminal 1 to limit the current to 1 milliampere.) Diode D_{10} isolates the base of transistor Q_7 from other signals when an external-inhibit signal is applied so that this signal is the highest priority command for normal operation. (Although grounding of terminal 6 creates a higher-priority inhibit function, this level is not compatible with normal DTL or TTL logic levels.) Transistor Q_7 may also be activated by turning off transistor Q_6 to allow current flow from the power supply through resistor R_7 and diode D_{10} into the base of Q_7. Transistor Q_6 is normally maintained in conduction by current that flows into its base through resistor R_2 and diodes D_8 and D_9 when transistor Q_1 is off.

Transistor Q_1 is a portion of the zero-crossing detector. When the voltage at terminal 5 is greater than +3 volts, current can flow through resistor R_1, diode D_6, the base-to-emitter junction of transistor Q_1, and diode D_4 to terminal 7 to turn on Q_1. This action inhibits the delivery of a gate-drive output signal at terminal 4. For negative voltages at terminal 5 that have magnitudes greater than 3 volts, the current flows through diode D_5, the emitter-to-base junction of transistor Q_1, diode D_3, and resistor R_1, and again turns on transistor Q_1. Transistor Q_1 is off only when the voltage at terminal 5 is less than the threshold voltage of approximately ±2 volts. When the integrated-circuit zero-voltage switch is connected as shown in Fig. 1, therefore, the output is a narrow pulse which is approximately centered about the zero-voltage time in the cycle, as shown in Fig. 3. In some applications, however, particularly those that use either slightly inductive or low-power loads, the thyristor load current does not reach the latching-current value* by the end of this pulse. An external capacitor C_X connected between terminal 5 and 7, as shown in Fig. 4, can be used to delay the pulse to accommodate such loads. The amount of pulse stretching and delay is shown in Figs. 5(a) and 5(b).

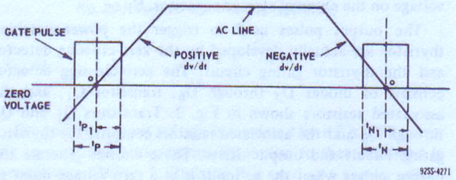


Fig. 3 – Waveform showing output-pulse duration of the zero-voltage switch.

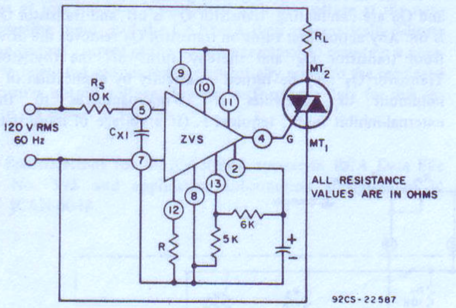


Fig. 4 – Use of a capacitor between terminals 5 and 7 to delay the output pulse of the zero-voltage switch.

Continuous gate current can be obtained if terminal 12 is connected to terminal 7 to disable the zero-crossing detector. In this mode, transistor Q_1 is always off. This mode of operation is useful when comparator operation is desired or when inductive loads must be switched. (If the capacitance in the load circuit is low, most RFI is eliminated.) Care must be taken to avoid overloading of the internal power supply in this mode. A sensitive-gate thyristor should be used, and a resistor should be placed between terminal 4 and the gate of the thyristor to limit the current, as pointed out later under **Special Application Considerations.**

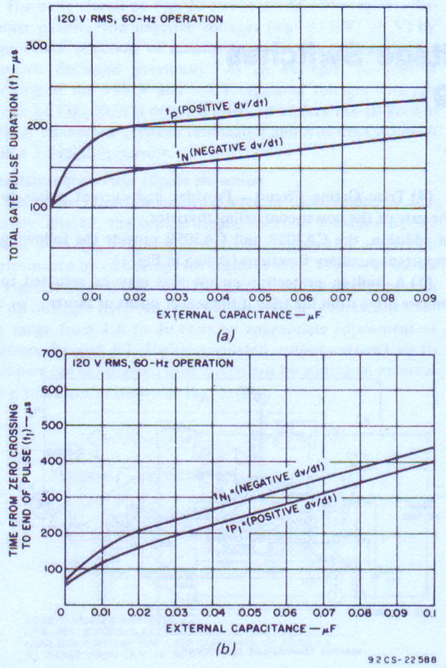
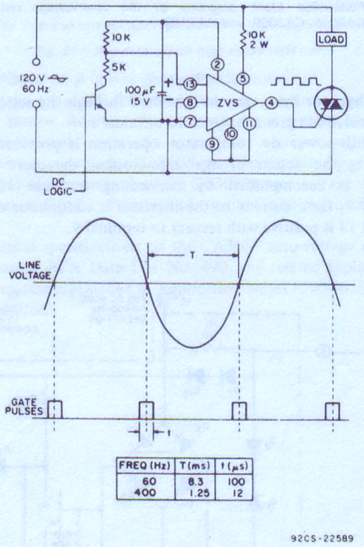


Fig. 5 – Curves showing effect of external capacitance on (a) the total output-pulse duration, and (b) the time from zero crossing to the end of the pulse.

Fig. 6 indicates the timing relationship between the line voltage and the zero-voltage- switch output pulses. At 60 Hz, the pulse is typically 100 microseconds wide; at 400 Hz, the pulse width is typically 12 microseconds. In the basic circuit shown, when the dc logic signal is "high", the output is disabled; when it is "low", the gate pulses are enabled.



FREQ (Hz)	T (ms)	t (μs)
60	8.3	100
400	1.25	12

Fig. 6 – Timing relationship between the output pulses of the RCA zero-voltage switch and the ac line voltage.

On-Off Sensing Amplifier

The discussion thus far has considered only cases in which pulses are present all the time or not at all. The differential sense amplifier consisting of transistors Q_2, Q_3, Q_4, and Q_5 (shown in Fig. 2) makes the zero-voltage switch a flexible power-control circuit. The transistor pairs Q_2-Q_4 and Q_3-Q_5 form a high-beta composite p-n-p transistors in which the emitters of transistors Q_4 and Q_5 act as the collectors of the composite devices. These two composite transistors are connected as a differential amplifier with resistor R_3 acting as a constant-current source. The relative current flow in the two "collectors" is a function of the difference in voltage between the bases of transistors Q_2 and Q_3. Therefore, when terminal 13 is more positive than terminal 9, little or no current flows in the "collector" of the transistor pair Q_2-Q_4. When terminal 13 is negative with respect to terminal 9, most of the current flows through that path, and none in terminal 8. When current flows in the transistor pair Q_2-Q_4, the path is from the supply through R_3, through the transistor pair Q_2-Q_4, through the base-emitter junction of transistor Q_1, and finally through the diode D_4 to terminal 7. Therefore, when V_{13} is equal to or more negative than V_9, transistor Q_1 is on, and the output is inhibited.

In the circuit shown in Fig. 1, the voltage at terminal 9 is derived from the supply by connection of terminals 10 and 11 to form a precision voltage divider. This divider forms one side of a transducer bridge, and the potentiometer R_p and the negative-temperature-coefficient (NTC) sensor form the other side. At low temperatures, the high resistance of the sensor causes terminal 13 to be positive with respect to terminal 9 so that the thyristor fires on every half-cycle, and power is applied to the load. As the temperature increases, the sensor resistance decreases until a balance is reached, and V_{13} approaches V_9. At this point, the transistor pair Q_2-Q_4 turns on and inhibits any further pulses. The controlled temperature is adjusted by variation of the value of the potentiometer R_p. For cooling service, either the positions of R_p and the sensor may be reversed or terminals 9 and 13 may be interchanged.

The low bias current of the sensing amplifier permits operation with sensor impedances of up to 0.1 megohm at balance without introduction of substantial error (i.e., greater than 5 per cent). The error may be reduced if the internal bridge elements, resistors R_4 and R_5, are not used, but are replaced with resistances which equal the sensor impedance. The minimum value of sensor impedance is restricted by the current drain on the internal power supply. Operation of the zero-voltage switch with low-impedance sensors is discussed later under **Special Application Considerations.** The voltage applied to terminal 13 must be greater than 1.8 volts at all times to assure proper operation.

Protection Circuit

A special feature of the CA3058 and CA3059 zero-voltage switches is the inclusion of an interlock type of circuit. This circuit removes power from the load by interrupting the thyristor gate drive if the sensor either shorts or opens. However, use of this circuit places certain constraints upon the user. Specifically, effective protection-circuit operation is dependent upon the following conditions:

(1) The circuit configuration of Fig. 1 is used, with an internal supply, no external load on the supply, and terminal 14 connected to terminal 13.

(2) The value of potentiometer R_p and of the sensor resistance must be between 2000 ohms and 0.1 megohm.

(3) The ratio of sensor resistance and R_p must be greater than 0.33 and less than 3.0 for all normal conditions. (If either of these ratios is not met with an unmodified sensor, a series resistor or a shunt resistor must be added to avoid undesired activation of the circuit.)

The protective feature may be applied to other systems when operation of the circuit is understood. The protection circuit consists of diodes D_{12} and D_{15} and transistor Q_{10}. Diode D_{12} activates the protection circuit if the sensor shown in Fig. 1 shorts or its resistance drops too low in value, as follows: Transistor Q_6 is on during an output pulse so that the junction of diodes D_8 and D_{12} is 3 diode drops (approximately 2 volts) above terminal 7. As long as V_{14} is more positive or only 0.15 volt negative with respect to that point, diode D_{12} does not conduct, and the circuit operates normally. If the voltage at terminal 14 drops to 1 volt, the anode of diode D_8 can have a potential of only 1.6 to 1.7 volts, and current does not flow through diodes D_8 and D_9 and transistor Q_6. The thyristor then turns off.

The actual threshold is approximately 1.2 volts at room temperature, but decreases 4 millivolts per degree C at higher temperatures. As the sensor resistance increases, the voltage at terminal 14 rises toward the supply voltage. At a voltage of approximately 6 volts, the zener diode D_{15} breaks down and turns on transistor Q_{10}, which then turns off transistor Q_6 and the thyristor. If the supply voltage is not at least 0.2 volt

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* The latching current is the minimum current required to sustain conduction immediately after the thyristor is switched from the off to the on state and the gate signal is removed.

more positive than the breakdown voltage of diode D_{15}, activation of the protection circuit is not possible. For this reason, loading the internal supply may cause this circuit to malfunction, as may selection of the wrong external supply voltage. Fig. 7 shows a guide for the proper operation of the protection circuit when an external supply is used with a typical integrated-circuit zero-voltage switch.

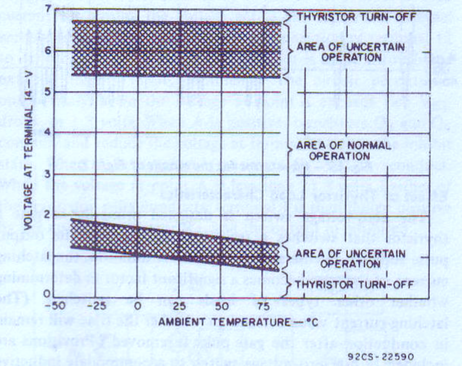


Fig. 7 – Operating regions for built-in protection circuits of a typical zero-voltage switch.

SPECIAL APPLICATION CONSIDERATIONS

As pointed out previously, the RCA integrated-circuit zero-voltage switches (CA3058, CA3059, and CA3079) are exceptionally versatile units that can be adapted for use in a wide-variety of power-control applications. Full advantage of this versatility can be realized, however, only if the user has a basic understanding of several fundamental considerations that apply to certain types of applications of the zero-voltage switches.

Operating-Power Options

Power to the zero-voltage switch may be derived directly from the ac line, as shown in Fig. 1, or from an external dc power supply connected between terminals 2 and 7, as shown in Fig. 8. When the zero-voltage switch is operated directly from the ac line, a dropping resistor R_S of 5,000 to 10,000 ohms must be connected in series with terminal 5 to limit the current in the switch circuit. The optimum value for this resistor is a function of the average current drawn from the internal dc power supply, either by external circuit elements or by the thyristor trigger circuits, as shown in Fig. 9. The chart shown in Fig. 1 indicates the value and dissipation rating of the resistor R_S for ac line voltages of 24, 120, 208 to 230, and 277 volts.

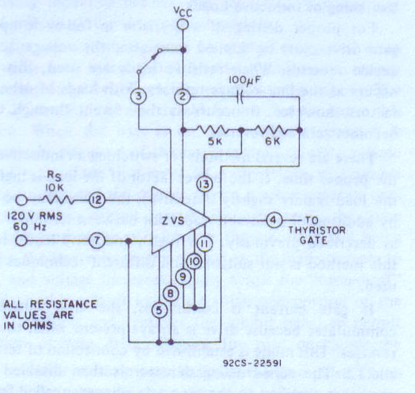


Fig. 8 – Operation of the zero-voltage switch from an external dc power supply connected between terminals 2 and 7.

Half-Cycling Effect

The method by which the zero-voltage switch senses the zero crossing of the ac power results in a half-cycling phenomenon at the control point. Fig. 10 illustrates this phenomenon. The zero-voltage switch senses the zero-voltage crossing every half-cycle, and an output, for example pulse No. 4, is produced to indicate the zero crossing. During the remaining 8.3 milliseconds, however, the differential amplifier in the zero-voltage switch may change state and inhibit any further output pulses. The uncertainty region of the differential amplifier, therefore, prevents pulse No. 5 from triggering the triac during the negative excursion of the ac line voltage.

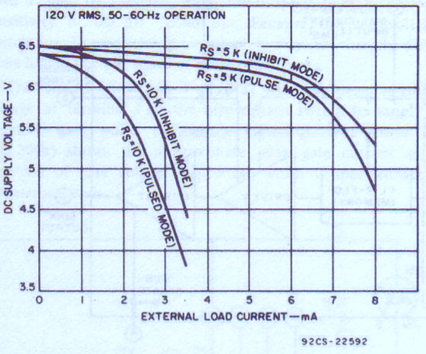


Fig. 9 – DC supply voltage as a function of external load current for several values of dropping resistance R_S.

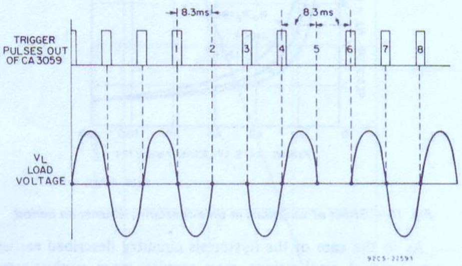
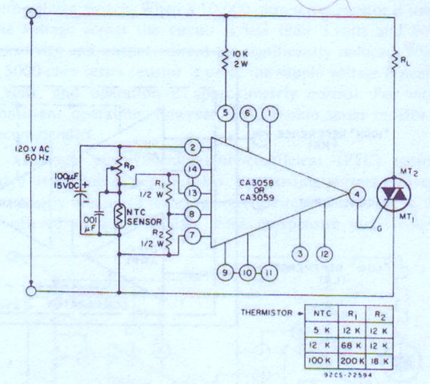


Fig. 10 – Half-cycling phenomenon in the zero-voltage switch.

When a sensor with low sensitivity is used in the circuit, the zero-voltage switch is very likely to operate in the linear mode. In this mode, the output trigger current may be sufficient to trigger the triac on the positive-going cycle, but insufficient to trigger the device on the negative-going cycle of the triac supply voltage. This effect introduces a half-cycling phenomenon, i.e., the triac is turned on during the positive half-cycle and turned off during the negative half-cycle.

Several techniques may be used to cope with the half-cycling phenomenon. If the user can tolerate some hysteresis in the control, then positive feedback can be added around the differential amplifier. Fig. 11 illustrates this technique. The tabular data in the figure lists the recommended values of resistors R_1 and R_2 for different sensor impedances at the control point.



NTC	R_1	R_2
5 K	12 K	12 K
12 K	68 K	12 K
100 K	200 K	18 K

Fig. 11 – CA3058 or CA3059 on-off controller with hysteresis.

If a significant amount (greater than ±10%) of controlled hysteresis is required, then the circuit shown in Fig. 12 may be employed. In this configuration, external transistor Q_1 can be used to provide an auxiliary timed-delay function.

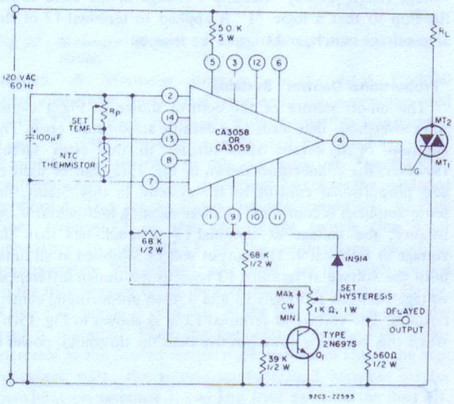


Fig. 12 – CA3058 or CA3059 on-off controller with controlled hysteresis.

For applications that require complete elimination of half-cycling without the addition of hysteresis, the circuit shown in Fig. 13 may be employed. This circuit uses a CA3098E integrated-circuit programmable comparator with a zero-voltage switch. A block diagram of CA3098E is shown in Fig. 14. Because the CA3098E contains an integral flip-flop, its output will be in either a "0" or "1" state. Consequently the zero-voltage switch cannot operate in the linear mode, and spurious half-cycling operation is prevented. When the signal-input voltage at terminal 8 of the CA3098E is equal to or less than the "low" reference voltage (LR), current flows from the power supply through resistor R_1 and R_2, and a logic "0" is

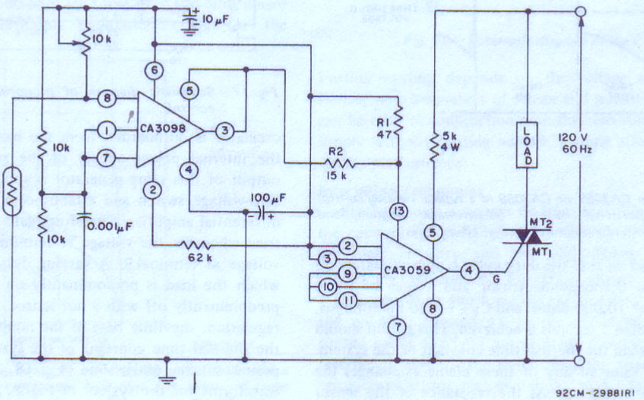


Fig. 13 – Sensitive temperature control.

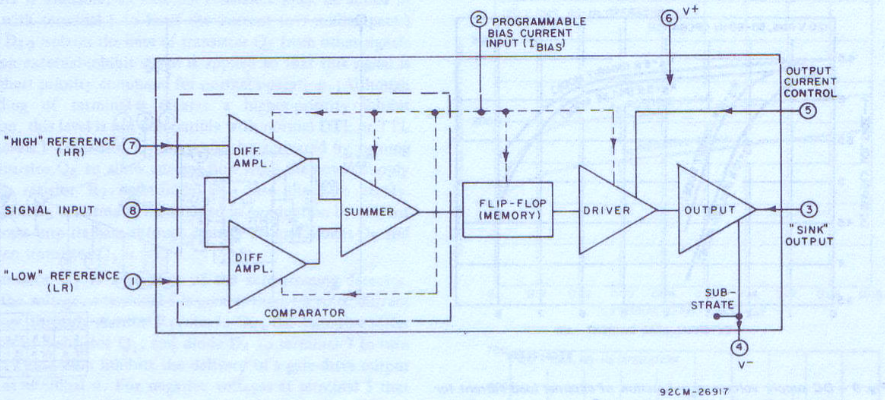
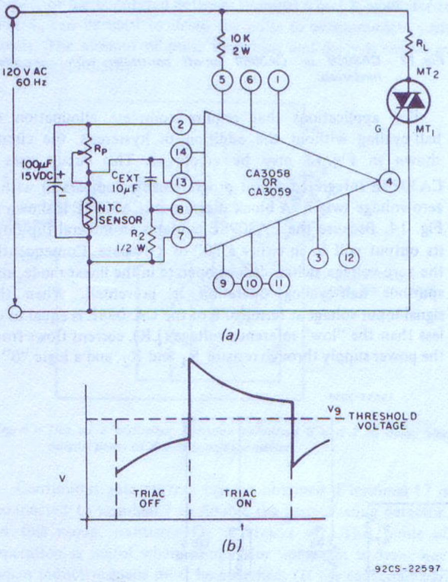


Fig. 14 – Block diagram of CA3098 programmable Schmitt trigger.

applied to terminal 13 of the zero-voltage switch. This condition turns off the triac. The triac remains off until the signal-input voltage rises to or exceeds the "high" reference voltage (HR), thereby effecting a change in the state of the flip-flop so that a logic "1" is applied to terminal 13 of the zero-voltage switch, and triggers the triac on.

"Proportional Control" Systems

The on-off nature of the control shown in Fig. 1 causes some overshoot that leads to a definite steady-state error. The addition of hysteresis adds further to this error factor. However, the connections shown in Fig. 15(a) can be used to add proportional control to the system. In this circuit, the sense amplifier is connected as a free-running multivibrator. At balance, the voltage at terminal 13 is much less than the voltage at terminal 9. The output will be inhibited at all times until the voltage at terminal 13 rises to the design differential voltage between terminals 13 and 9; then proportional control resumes. The voltage at terminal 13 is as shown in Fig. 15(b). When this voltage is more positive than the threshold, power is applied to the load so that the duty cycle is approximately 50 per cent. With a 0.1 megohm sensor and values of R_P = 0.1 megohm, R_2 = 10,000 ohms, and C_{EXT} = 10 microfarads, a period greater than 3 seconds is achieved. This period should be much shorter than the thermal time constant of the system. A change in the value of any of these elements changes the period, as shown in Fig. 16. As the resistance of the sensor changes, the voltage on terminal 13 moves relative to V_9. A cooling sensor moves V_{13} in a positive direction. The triac is on for a larger portion of the pulse cycle and increases the average power to the load.



(a)

(b)

Fig. 15 – Use of the CA3058 or CA3059 in a typical heating control with proportional control: (a) schematic diagram, and (b) waveform of voltage at terminal 13.

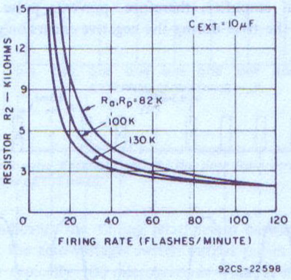


Fig. 16 – Effect of variations in time-constant elements on period.

As in the case of the hysteresis circuitry described earlier, some special applications may require more sophisticated systems to achieve either very precise regions of control or very long periods.

Zero-voltage switching control can be extended to applications in which it is desirable to have constant control of the temperature and a minimization of system hysteresis. A closed-loop top-burner control in which the temperature of the cooking utensil is sensed and maintained at a particular value is a good example of such an application; the circuit for this control is shown in Fig. 17. In this circuit, a unijunction oscillator is outboarded from the basic control by means of the internal power supply of the zero-voltage switch. The output of this ramp generator is applied to terminal 9 of the zero-voltage switch and establishes a varied reference to the differential amplifier. Therefore, gate pulses are applied to the triac whenever the voltage at terminal 13 is greater than the voltage at terminal 9. A varying duty cycle is established in which the load is predominantly on with a cold sensor and predominantly off with a hot sensor. For precise temperature regulation, the time base of the ramp should be shorter than the thermal time constant of the system but longer than the period of the 60-Hz line. Fig. 18, which contains various waveforms for the system of Fig. 17, indicates that a typical variance of ±0.5°C might be expected at the sensor contact to the utensil. Overshoot of the set temperature is minimized with this approach, and scorching of any type is minimized.

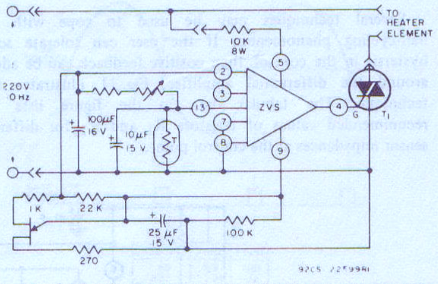


Fig. 17 – Schematic diagram of proportional zero-voltage-switching control.

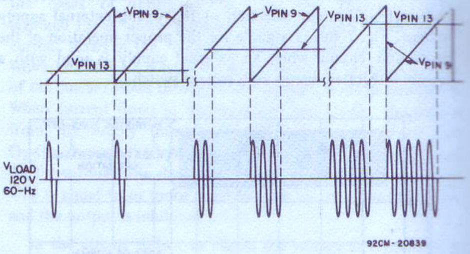


Fig. 18 – Waveforms for the circuit of Fig. 17.

Effect of Thyristor Load Characteristics

The zero-voltage switch is designed primarily to gate a thyristor that switches a resistive load. Because the output pulse supplied by the switch is of short duration, the latching current of the triac becomes a significant factor in determining whether other types of loads can be switched. (The latching-current value determines whether the triac will remain in conduction after the gate pulse is removed.) Provisions are included in the zero-voltage switch to accommodate inductive loads and low-power loads. For example, for loads that are less than approximately 4 amperes rms or that are slightly inductive, it is possible to retard the output pulse with respect to the zero-voltage crossing by insertion of the capacitor C_x from terminal 5 to terminal 7. The insertion of capacitor C_x permits switching of triac loads that have a slight inductive component and that are greater than approximately 200 watts (for operation from an ac line voltage of 120 volts rms). However, for loads less than 200 watts (for example, 70 watts), it is recommended that the user employ the T2300B* sensitive-gate triac with the zero-voltage switch because of the low latching-current requirement of this triac.

For loads that have a low power factor, such as a solenoid valve, the user may operate the zero-voltage switch in the dc mode. In this mode, terminal 12 is connected to terminal 7, and the zero-crossing detector is inhibited. Whether a "high" or "low" voltage is produced at terminal 4 is then dependent only upon the state of the differential comparator within the integrated-circuit zero-voltage switch, and not upon the zero crossing of the incoming line voltage. Of course, in this mode of operation, the zero-voltage switch no longer operates as a zero-voltage switch. However, for many applications that involve the switching of low-current inductive loads, the amount of RFI generated can frequently be tolerated.

For switching of high-current inductive loads, which must be turned on at zero line current, the triggering technique employed in the dual-output over-under temperature controller and the transient-free switch controller described subsequently in this Note is recommended.

Switching of Inductive Loads

For proper driving of a thyristor in full-cycle operation, gate drive must be applied soon after the voltage across the device reverses. When resistive loads are used, this reversal occurs as the line voltage reverses. With loads of other power factors, however, it occurs as the current through the load becomes zero and reverses.

There are several methods for switching an inductive load at the proper time. If the power factor of the load is high (i.e., if the load is only slightly inductive), the pulse may be delayed by addition of a suitable capacitor between terminals 5 and 7, as described previously. For highly inductive loads, however, this method is not suitable, and different techniques must be used.

If gate current is continuous, the triac automatically commutates because drive is always present when the voltage reverses. This mode is established by connection of terminals 7 and 12. The zero-crossing detector is then disabled so that current is supplied to the triac gate whenever called for by the sensing amplifier. Although the RFI-eliminating function of the zero-voltage switch is inhibited when the zero-crossing detector is disabled, there is no problem if the load is highly inductive because the current in the load cannot change abruptly.

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* Formerly RCA 40526

Circuits that use a sensitive-gate triac to shift the firing point of the power triac by approximately 90 degrees have been designed. If the primary load is inductive, this phase shift corresponds to firing at zero current in the load. However, changes in the power factor of the load or tolerances of components will cause errors in this firing time.

The circuit shown in Fig. 19 uses a CA3086 integrated-circuit transistor array to detect the absence of load current by sensing the voltage across the triac. The internal zero-crossing detector is disabled by connection of terminal 12 to terminal 7, and control of the output is made through the external inhibit input, terminal 1. The circuit permits an output only when the voltage at point A exceeds two V_{BE} drops, or 1.3 volts. When A is positive, transistors Q_3 and Q_4 conduct and reduce the voltage at terminal 1 below the inhibit state. When A is negative, transistors Q_1 and Q_2 conduct. When the voltage at point A is less than ±1.3 volts, neither of the transistor pairs conducts; terminal 1 is then pulled positive by the current in resistor R_3, and the output in inhibited.

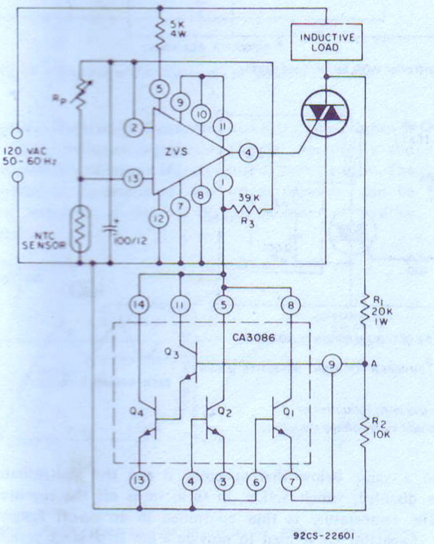


Fig. 19 – Use of the CA3058 or CA3059 together with CA3086 for switching inductive loads.

The circuit shown in Fig. 19 forms a pulse of gate current and can supply high peak drive to power traics with low average current drain on the internal supply. The gate pulse will always last just long enough to latch the thyristor so that there is no problem with delaying the pulse to an optimum time. As in other circuits of this type, RFI results if the load is not suitably inductive because the zero-crossing detector is disabled and initial turn-on occurs at random.

The gate pulse forms because the voltage at point A when the thyristor is on is less than 1.3 volts: therefore, the output of the zero-voltage switch is inhibited, as described above. The resistor divider R_1 and R_2 should be selected to assure this condition. When the triac is on, the voltage at point A is approximately one-third of the instantaneous on-state voltage (v_T) of the thyristor. For most RCA thyristors, v_T (max) is less than 2 volts, and the divider shown is a conservative one. When the load current passes through zero, the triac commutates and turns off. Because the circuit is still being driven by the line voltage, the current in the load attempts to reverse, and voltage increases rapidly across the "turned-off" triac. When this voltage exceeds 4 volts, one portion of the CA3086 conducts and removes the inhibit signal to permit application of gate drive. Turning the triac on causes the voltage across it to drop and thus ends the gate pulse. If the latching current has not been attained, another gate pulse forms, but no discontinuity in the load current occurs.

Provision of Negative Gate Current

Triacs trigger with optimum sensitivity when the polarity of the gate voltage and the voltage at the main terminal 2 are similar (I^+ and II^- modes). Sensitivity is degraded when the polarities are opposite (I^- and III^+ modes). Although RCA triacs are designed and specified to have the same sensitivity in both I^- and III^+ modes, some other types have very poor sensitivity in the III^+ condition. Because the zero-voltage switch supplies positive gate pulses, it may not directly drive some higher-current triacs of these other types.

The circuit shown in Fig. 20(a) uses the negative-going voltage at terminal 3 of the zero-voltage switch to supply a negative gate pulse through a capacitor. The curve in Fig. 20(b) shows the approximate peak gate current as a function of gate voltage V_G. Pulse width is approximately 80 microseconds.

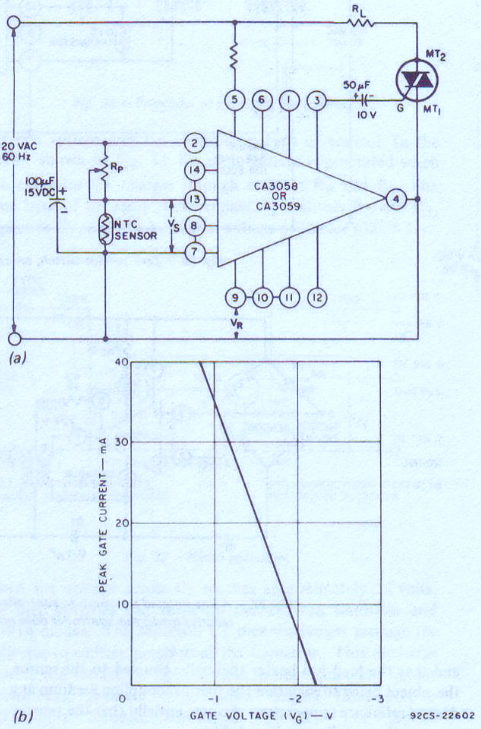


Fig. 20 – Use of the CA3058 or CA3059 to provide negative gate pulses: (a) schematic diagram; (b) peak gate current (at terminal 3) as a function of gate voltage.

Operation with Low-Impedance Sensors

Although the zero-voltage switch can operate satisfactorily with a wide range of sensors, sensitivity is reduced when sensors with impedances greater than 20,000 ohms are used. Typical sensitivity is one per cent for a 5000-ohm sensor and increases to three per cent for a 0.1-megohm sensor.

Low-impedance sensors present a different problem. The sensor bridge is connected across the internal power supply and causes a current drain. A 5000-ohm sensor with its associated 5000-ohm series resistor draws less than 1 milliampere. On the other hand, a 300-ohm sensor draws a current of 8 to 10 milliampers from the power supply.

Fig. 21 shows the 600-ohm load line of a 300-ohm sensor on a redrawn power-supply regulation curve for the zero-voltage switch. When a 10,000-ohm series resistor is used, the voltage across the circuit is less than 3 volts and both sensitivity and output current are significantly reduced. When a 5000-ohm series resistor is used, the supply voltage is nearly 5 volts, and operation is approximately normal. For more consistent operation, however, a 4000-ohm series resistor is recommended.

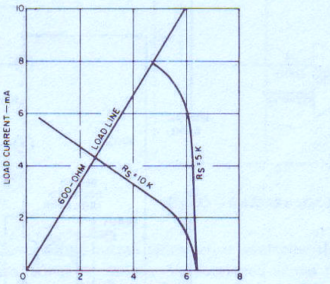


Fig. 21 – Power-supply regulation of the CA3058 or CA3059 with a 300-ohm sensor (600-ohm load) for two values of series resistor.

Although positive-temperature-coefficient (PTC) sensors rated at 5 kilohms are available, the existing sensors in ovens are usually of a much lower value. The circuit shown in Fig. 22 is offered to accommodate these inexpensive metal-wound sensors. A schematic diagram of the RCA CA3080 integrated-circuit operational transconductance amplifier used in Fig. 22, is shown in Fig. 23. With an amplifier bias current, I_{ABC}, of 100 microamperes, a forward transconductance of 2 milliohms is achieved in this configuration. The CA3080 switches when the voltage at terminal 2 exceeds the voltage at terminal 3. This action allows the sink current, I_s, to flow from terminal 13 of the zero-voltage switch (the input impedance to terminal 13 of the zero-voltage switch is approximately 50 kilohms); gate pulses are no longer applied to the triac because Q_2 of the zero-voltage switch is on. Hence, if the PTC sensor is cold, i.e., in the low resistance state, the load is energized. When the temperature of the PTC sensor increases to the desired temperature, the sensor enters the high resistance state, the voltage on terminal 2 becomes greater than that on terminal 3, and the triac switches the load off.

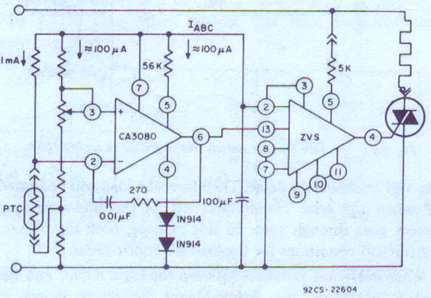


Fig. 22 – Schematic diagram of circuit for use with low-resistance sensor.

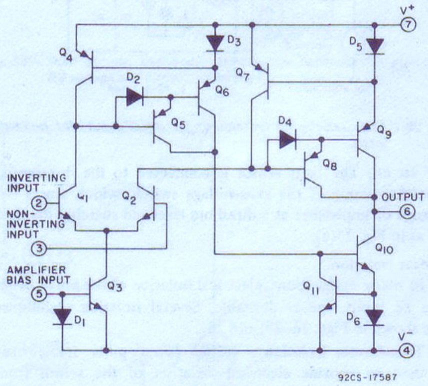


Fig. 23 – Schematic diagram of the CA3080.

Further cycling depends on the voltage across the sensor. Hence, very low values of sensor and potentiometer resistance can be used in conjunction with the zero-voltage switch power supply without causing adverse loading effects and impairing system performance.

Interfacing Techniques

Fig. 24 shows a system diagram that illustrates the role of the zero-voltage switch and thyristor as an interface between the logic circuitry and the load. There are several basic interfacing techniques. Fig. 25(a) shows the **direct input** technique. When the logic output transistor is switched from the on state (saturated) to the off state, the load will be turned on at the next zero-voltage crossing by means of the interfacing zero-voltage switch and the triac. When the logic output transistor is switched back to the on state, zero-crossing pulses from the zero-voltage switch to the triac

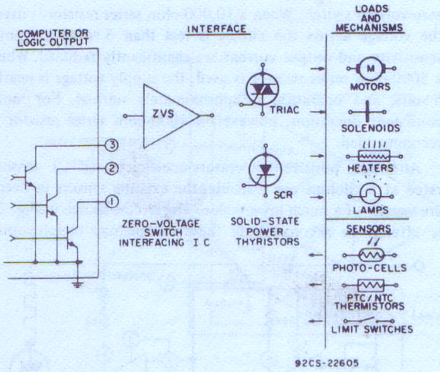


Fig. 24 – The zero-voltage switch and thyristor as an interface.

gate will immediately cease. Therefore, the load will be turned off when the triac commutates off as the sine-wave load current goes through zero. In this manner, both the turn-on and turn-off conditions for the load are controlled.

When electrical isolation between the logic circuit and the load is necessary, the **isolated-input** technique shown in Fig. 25(b) is used. In the technique shown, optical coupling is used to achieve the necessary isolation. The logic output transistor switches the light-source portion of the isolator. The light-sensor portion changes from a high impedance to a low impedance when the logic output transistor is switched from off to on. The light sensor is connected to the differential amplifier input of the zero-voltage switch, which senses the change of impedance at a threshold level and switches the load on as in Fig. 25(a).

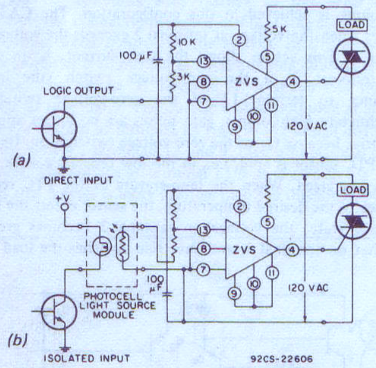


Fig. 25 – Basic interfacing techniques: (a) direct input; (b) isolated input.

Sensor Isolation

In many applications, electrical isolation of the sensor from the ac input line is desirable. Several isolation techniques are shown in Figs. 26, 27, and 28.

Transformer Isolation – In Fig. 26, a pulse transformer is used to provide electrical isolation of the sensor from incoming ac power lines. The pulse transformer T_1 isolates the sensor from terminal No. 1 of the triac Y_1, and transformer T_2 isolates the CA3058 or CA3059 from the power lines. Capacitor C_1 shifts the phase of the output pulse at terminal No. 4 in order to retard the gate pulse delivered to triac Y_1 to compensate for the small phase-shift introduced by transformer T_1.

Many applications require line isolation but not zero-voltage switching. A line-isolated temperature controller for use with inductive or resistive loads that does not include zero-voltage switching is shown in Fig. 27.

In temperature monitoring or control applications the sensor may be a temperature-dependent element such as a resistor, thermistor, or diode. The load may be a lamp, bell, horn, recorder or other appropriate device connected in a feedback relationship to the sensor.

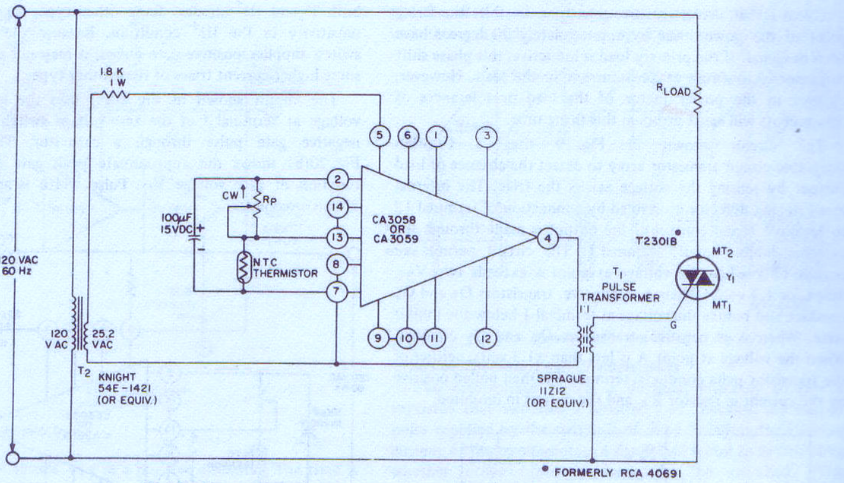
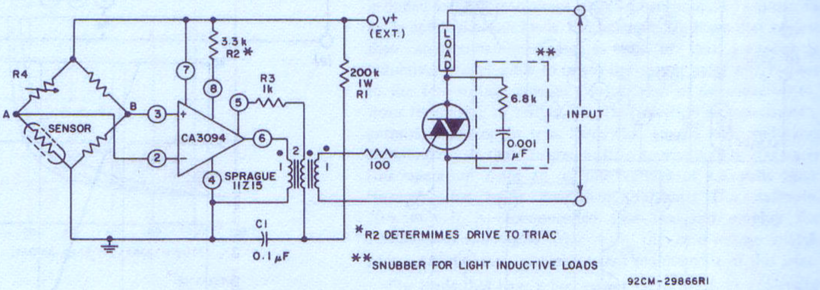


Fig. 26 – Zero-voltage switch, on-off controller with an isolated sensor.



*R2 DETERMIMES DRIVE TO TRIAC

**SNUBBER FOR LIGHT INDUCTIVE LOADS

Fig. 27 – A line-isolated temperature controller for use with inductive or resistive loads; this controller does not include zero-voltage switching.

For the purpose of the following explanation, assume that the sensor is a resistor having a negative temperature coefficient and that the load is a heater thermally coupled to the sensor, the object being to maintain the thermal-coupling medium at a desired reference temperature. Assume initially that the temperature at the coupling medium is low.

The operating potentials applied to the bridge circuit produce a common-mode potential, V_{CM}, at the input terminals of the CA3094. Assuming the bridge to have been initially balanced (by adjustment of R4), the potential at point A will increase when temperature is low since it was assumed that the sensor has a negative temperature coefficient. The potential at the noninverting terminal, being greater than that at the inverting terminal at the amplifier, causes the multivibrator to oscillate at approximately 10 kHz. The oscillations are transformer-coupled through a current-limiting resistor to the gate of the thyristor, and trigger it into conduction.

When the thyristor conducts, the load receives ac input power, which tends to increase the temperature of the sensor. This temperature increase decreases the potential at point A to a value below that at point B and the multivibrator is disabled, which action, in turn, turns off the thyristor. The temperature is thus controlled in an on-off fashion.

Capacitor C_1 is used to provide a low impedance path to ground for feedback-induced signals at terminal No. 5 while blocking the direct current bias provided by resistor R1. Resistor R2 provides current limiting. Resistor R3 limits the secondary current of the transformer to prevent excessive current flow to the control terminal of the CA3094.

Photocoupler Isolation – In Fig. 28, a photocoupler provides electrical isolation of the sensor logic from the incoming ac power lines. When a logic "1" is applied at the input of the photocoupler, the triac controlling the load will be turned on whenever the line voltage passes through zero. When a logic "0" is applied to the photocoupler, the triac will turn off and remain off until a logic "1" appears at the input of the photocoupler.

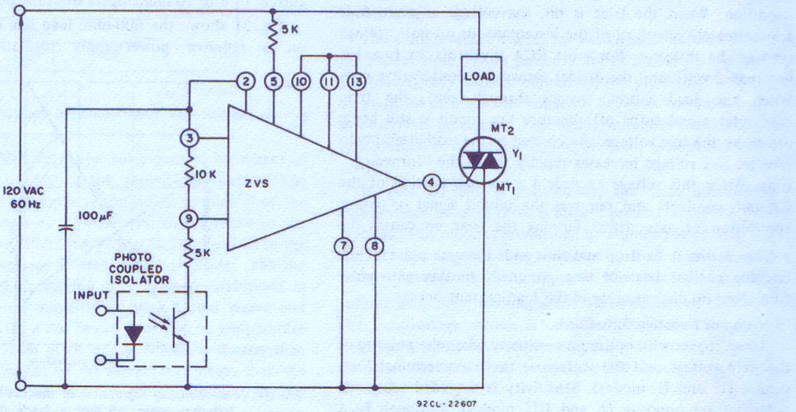


Fig. 28 – Zero-voltage switch, on-off controller with photocoupler.

TEMPERATURE CONTROLLERS

Fig. 29 shows a triac used in an on-off temperature-controller configuration. The triac is turned on at zero voltage whenever the voltage V_s exceeds the reference voltage V_r. The transfer characteristic of this system, shown in Fig. 30(a), indicates significant thermal overshoots and undershoots, a well-known characteristic of such a system. The differential or hysteresis of this system, however, can be further increased, if desired, by the addition of positive feedback.

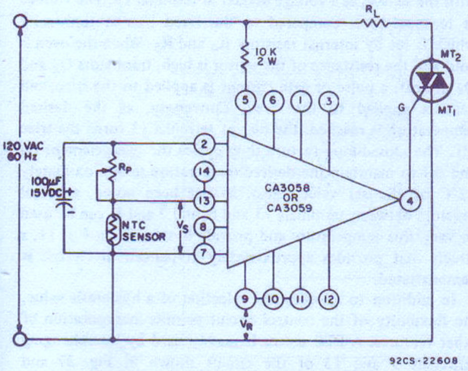


Fig. 29 – CA3058 or CA3059 on-off temperature controller.

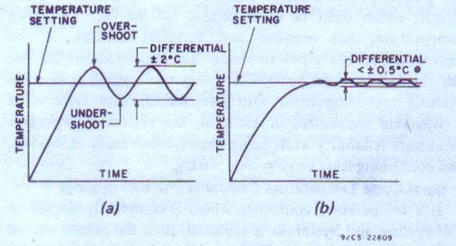


Fig. 30 – Transfer characteristics of (a) on-off and (b) proportional control systems.

For precise temperature-control applications, the proportional-control technique with synchronous switching is employed. The transfer curve for this type of controller is shown in Fig. 30(b). In this case, the duty cycle of the power supplied to the load is varied with the demand for heat required and the thermal time constant (inertia) of the system. For example, when the temperature setting is increased in an on-off type of controller, full power (100 per cent duty cycle) is supplied to the system. This effect results in significant temperature excursions because there is no anticipatory circuit to reduce the power gradually before the actual set temperature is achieved. However, in a proportional control technique, less power is supplied to the load (reduced duty cycle) as the error signal is reduced (sensed temperature approaches the set temperature).

Before such a system is implemented, a time base is chosen so that the on-time of the triac is varied within this time base. The ratio of the on-to-off time of the triac within this time interval depends on the thermal time constant of the system and the selected temperature setting. Fig. 31 illustrates the principle of proportional control. For this operation, power is supplied to the load until the ramp voltage reaches a value greater than the dc control signal supplied to the opposite side of the differential amplifier. The triac then remains off for the remainder of the time-base period. As a result, power is "proportioned" to the load in a direct relation to the heat demanded by the system.

For this application, a simple ramp generator can be realized with a minimum number of active and passive components. A ramp having good linearity is not required for proportional operation because of the nonlinearity of the thermal system and the closed-loop type of control. In the circuit shown in Fig. 32, the ramp voltage is generated when the capacitor C_1 charges through resistors R_0 and R_1. The time base of the ramp is determined by resistors R_2 and R_3, capacitor C_2, and the breakover voltage of the D3202U* diac.

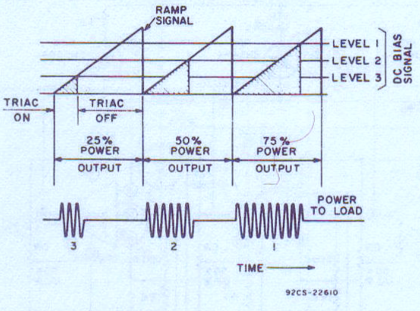


Fig. 31 – Principles of proportional control.

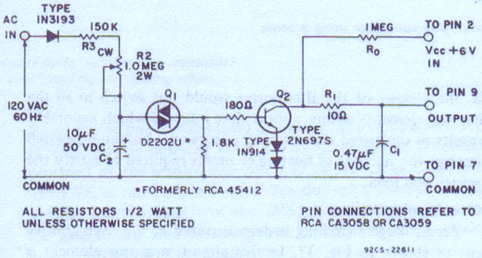


Fig. 32 – Ramp generator.

When the voltage across C_2 reaches approximately 32 volts, the diac switches and turns on the 2N697S transistor and 1N914 diodes. The capacitor C_1 then discharges through the collector-to-emitter junction of the transistor. This discharge time is the retrace or flyback time of the ramp. The circuit shown can generate ramp times ranging from 0.3 to 2.0 seconds through adjustment of R_2. For precise temperature regulation, the time base of the ramp should be shorter than the thermal time constant of the system, but long with respect to the period of the 60-Hz line voltage. Fig. 33 shows a triac connected for the proportional mode.

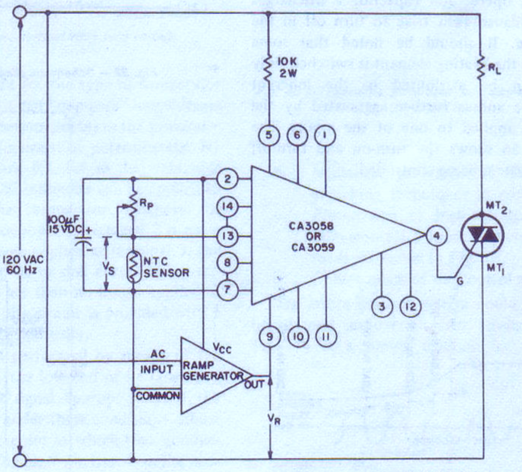


Fig. 33 – CA3058 or CA3059 proportional temperature controller.

Fig. 34(a) shows a dual-output temperature controller that drives two triacs. When the voltage V_s developed across the temperature-sensing network exceeds the reference voltage V_{R1}, motor No. 1 turns on. When the voltage across the network drops below the reference voltage V_{R2}, motor No. 2 turns on. Because the motors are inductive, the currents I_{M1} lag the incoming line voltage. The motors, however, are switched by the triacs at zero current, as shown in Fig. 34(b).

The problem of driving inductive loads such as these motors by the narrow pulses generated by the zero-voltage switch is solved by use of the sensitive-gate RCA-40526 triac. The high sensitivity of this device (3 milliamperes maximum) and low latching current (approximately 9 milliamperes) permit synchronous operation of the temperature-controller circuit. In Fig. 34(a), it is apparent that, though the gate pulse V_g of triac Y_1 has elapsed, triac Y_2 is switched on by the current through R_{L1}. The low latching current of the RCA-40526 triac results in dissipation of only 2 watts in R_{L1}, as opposed to 10 to 20 watts when devices that have high latching currents are used.

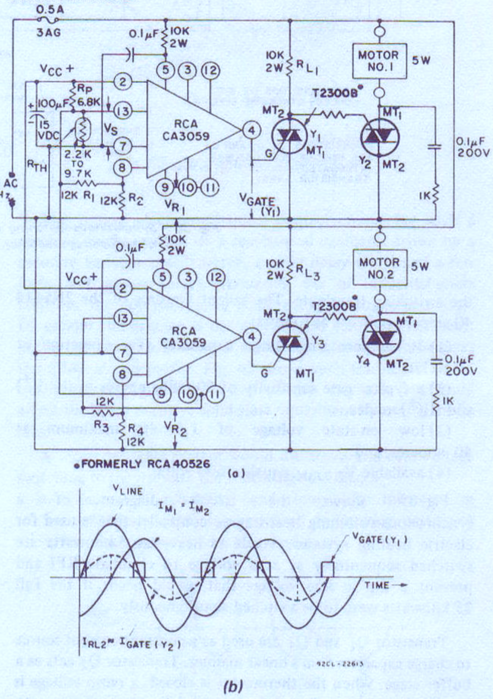


Fig. 34 – Dual output, over-under temperature controller (a) circuit, (b) voltage and current waveforms.

Electric-Heat Application

For electric-heating applications, the RCA-2N5444 40-ampere triac and the zero-voltage switch constitute an optimum pair. Such a combination provides synchronous switching and effectively replaces the heavy-duty contactors which easily degrade as a result of pitting and wearout from

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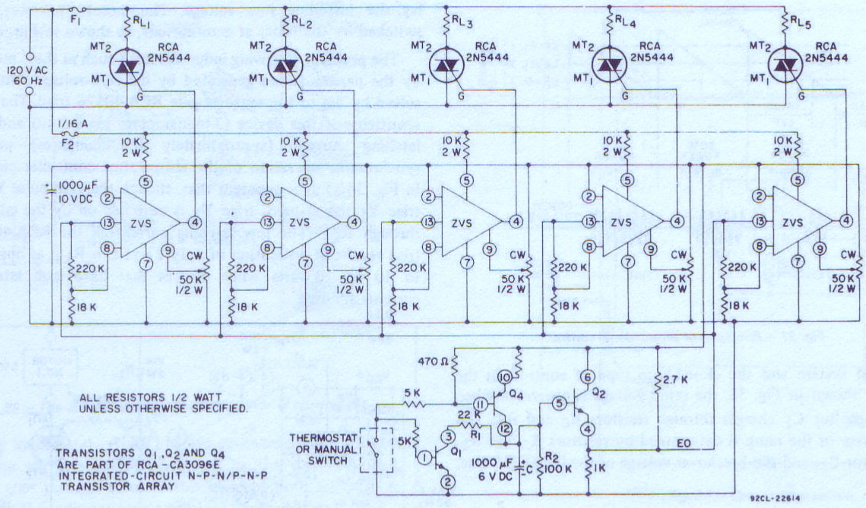
* Formerly RCA 45412



ALL RESISTORS 1/2 WATT UNLESS OTHERWISE SPECIFIED.

TRANSISTORS Q_1, Q_2 AND Q_4 ARE PART OF RCA-CA3096E INTEGRATED-CIRCUIT N-P-N/P-N-P TRANSISTOR ARRAY

Fig. 35 – Synchronous-switching heat-staging controller using a series of zero-voltage switches.

the switching transients. The salient features of the 2N5444 40-ampere triac are as follows:

(1) 300-ampere single-surge capability (for operation at 60-Hz),

(2) a typical gate sensitivity of 20 milliamperes in the $I^{(+)}$ and $III^{(+)}$ modes,

(3) low on-state voltage of 1.5 volts maximum at 40 amperes, and

(4) available V_{DROM} equal to 600 volts.

Fig. 35 shows the circuit diagram of a synchronous-switching heat-staging controller that is used for electric heating systems. Loads as heavy as 5 kilowatts are switched sequentially at zero voltage to eliminate RFI and prevent a dip in line voltage that would occur if the full 25 kilowatts were to be switched simultaneously.

Transistor Q_1 and Q_4 are used as a constant-current source to charge capacitor C in a linear manner. Transistor Q_2 acts as a buffer stage. When the thermostat is closed, a ramp voltage is provided at output E_o. At approximately 3-second intervals, each 5-kilowatt heating element is switched onto the power system by its respective triac. When there is no further demand for heat, the thermostat opens, and capacitor C discharges through R_1 and R_2 to cause each triac to turn off in the reverse heating sequence. It should be noted that some half-cycling occurs before the heating element is switched fully on. This condition can be attributed to the inherent dissymmetry of the triac and is further aggravated by the slow-rising ramp voltage applied to one of the inputs. The timing diagram in Fig. 36 shows the turn-on and turn-off sequence of the heating system being controlled.

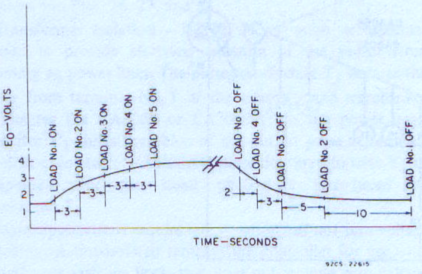


Fig. 36 – Ramp-voltage waveform for the heat-staging controller.

Seemingly, the basic method shown in Fig. 35 could be modified to provide proportional control in which the number of heating elements switched into the system, under any given thermal load, would be a function of the BTU's required by the system or the temperature differential between an indoor and outdoor sensor within the total system environment. That is, the closing of the thermostat would not switch in all the heating elements within a short time interval, which inevitably results in undesired temperature excursions, but would switch in only the number of heating elements required to satisfy the actual heat load.

Oven/Broiler Control

Zero-voltage switching is demonstrated in the oven control circuit shown in Fig. 37. In this circuit, a sensor element is included in the oven to provide a closed-loop system for accurate control of the oven temperature.

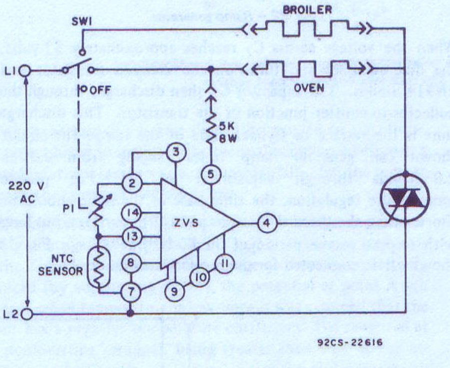


Fig. 37 – Schematic diagram of basic oven control.

As shown in Fig. 37, the temperature of the oven can be adjusted by means of potentiometer R_1, which acts, together with the sensor, as a voltage divider at terminal 13. The voltage at terminal 13 is compared to the fixed bias at terminal 9 which is set by internal resistors R_4 and R_5. When the oven is cold and the resistance of the sensor is high, transistors Q_2 and Q_4 are off, a pulse of gate current is applied to the triac, and heat is applied to the oven. Conversely, as the desired temperature is reached, the bias at terminal 13 turns the triac off. The closed-loop feature then cycles the oven element on and off to maintain the desired temperature to approximately ±2°C of the set value. Also, as has been noted, external resistors between terminals 13 and 8, and 7 and 8, can be used to vary this temperature and provide hysteresis. In Fig. 11, a circuit that provides approximately 10-per-cent hysteresis is demonstrated.

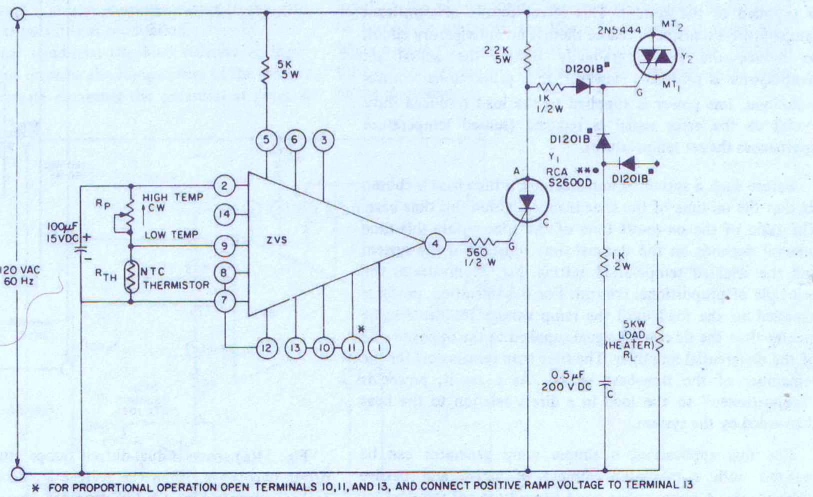
In addition to allowing the selection of a hysteresis value, the flexibility of the control circuit permits incorporation of other features. A PTC sensor is readily used by interchanging terminals 9 and 13 of the circuit shown in Fig. 37 and substituting the PTC for the NTC sensor. In both cases, the sensor element is directly returned to the system ground or common, as is often desired. Terminal 9 can be connected by external resistors to provide for a variety of biasing, e.g., to match a lower-resistance sensor for which the switching-point voltage has been reduced to maintain the same sensor current.

To accommodate the self-cleaning feature, external switching, which enables both broiler and oven units to be paralleled, can easily be incorporated in the design. Of course, the potentiometer must be capable of a setting such that the sensor, which must be characterized for the high, self-clean temperature, can monitor and establish control of the high-temperature, self-clean mode. The ease with which this self-clean mode can be added makes the over-all solid-state systems cost-competitive with electromechanical systems of comparable capability. In addition, the system incorporates solid-state reliability while being neater, more easily calibrated, and containing less-costly system wiring.

Integral-Cycle Temperature Controller (No half-cycling)

If a temperature controller which is completely devoid of half-cycling and hysteresis is required, then the circuit shown in Fig. 38 may be used. This type of circuit is essential for applications in which half-cycling and the resultant dc component could cause overheating of a power transformer on the utility lines.

In the integral-cycle controller, when the temperature being controlled is low, the resistance of the thermistor is high, and an output signal at terminal 4 of zero volts is obtained. The SCR (Y_1), therefore, is turned off. The triac (Y_2) is then triggered directly from the line on positive cycles of the ac voltage. When Y_2 is triggered and supplies power to the load R_L, capacitor C is charged to the peak of the input voltage.



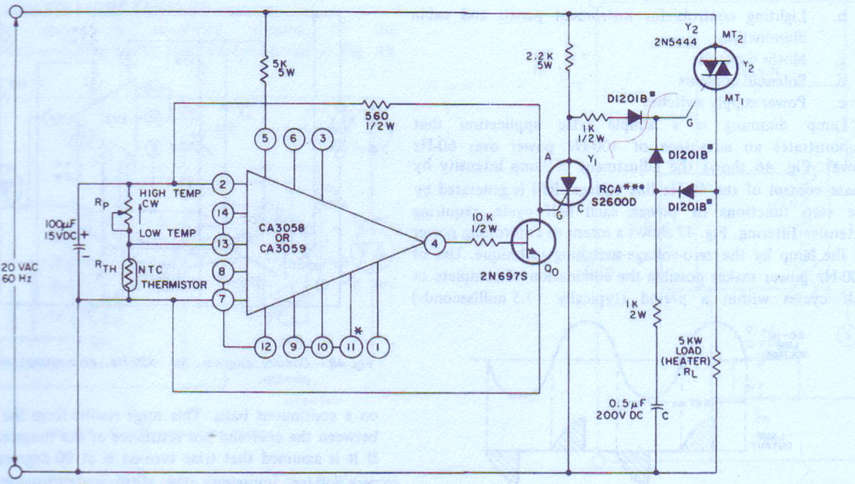
* FOR PROPORTIONAL OPERATION OPEN TERMINALS 10, 11, AND 13, AND CONNECT POSITIVE RAMP VOLTAGE TO TERMINAL 13

** SELECTED FOR I_{GT} = 6 mA MAXIMUM.

▪ FORMERLY RCA 44003

● FORMERLY RCA 40655

Fig. 38 – Integral-cycle temperature controller in which half-cycling effect is eliminated.



* FOR PROPORTIONAL OPERATION OPEN TERMINALS 9,10 AND 11 AND CONNECT POSTIVE RAMP VOLTAGE TO TERMINAL 9
**SELECTED FOR I_{GT} = 6 mA MAXIMUM
▪FORMERLY RCA 44003
●FORMERLY RCA 40655

92CM-22618

Fig. 39 – CA3058 or CA3059 integral-cycle temperature controller that features a protection circuit and no half-cycling effect.

When the ac line swings negative, capacitor C discharges through the triac gate to trigger the triac on the negative half-cycle. The diode-resistor-capacitor "slaving network" triggers the triac on negative half-cycle to provide only **integral cycles** of ac power to the load.

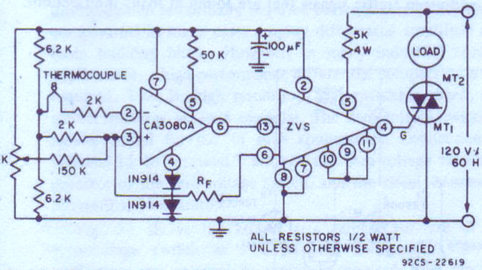
When the temperature being controlled reaches the desired value, as determined by the thermistor, then a positive voltage level appears at terminal 4 of the zero-voltage switch. The SCR then starts to conduct at the beginning of the positive input cycle to shunt the trigger current away from the gate of the triac. The triac is then turned off. The cycle repeats when the SCR is again turned OFF by the zero-voltage switch.

The circuit shown in Fig. 39 is similar to the configuration in Fig. 38 except that the protection circuit incorporated in the zero-voltage switch can be used. In this new circuit, the NTC sensor is connected between terminals 7 and 13, and transistor Q_o inverts the signal output at terminal 4 to nullify the phase reversal introduced by the SCR (Y_1). The internal power supply of the zero-voltage switch supplies bias current to transistor Q_o.

Of course, the circuit shown in Fig. 39 can readily be converted to a **true proportional integral-cycle temperature controller** simply by connection of a positive-going ramp voltage to terminal 9 (with terminals 10 and 11 open), as previously discussed in this Note.

Thermocouple Temperature Control

Fig. 40 shows the CA3080A operating as a pre-amplifier for the zero-voltage switch to form a zero-voltage switching circuit for use with thermocouple sensors.

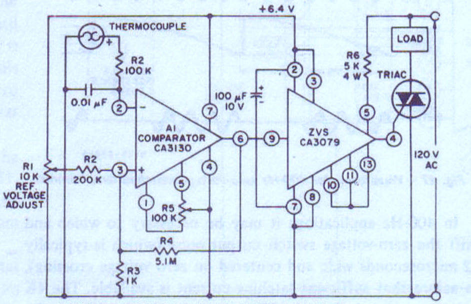


92CS-22619

Fig. 40 – Thermocouple temperature control with zero-voltage switching.

Thermocouple Temperature Control with Zero-Voltage Load Switching

Fig. 41 shows the circuit diagram of a thermocouple temperature control system using zero-voltage load switching. It should be noted that one terminal of the thermocouple is connected to one leg of the supply line. Consequently, the thermocouple can be "ground-referenced", provided the appropriate leg of the ac line is maintained at ground. The comparator, A_1 (a CA3130), is powered from a 6.4-volt source of potential provided by the zero-voltage-switch (ZVS) circuit (a CA3079). The ZVS, in turn, is powered off-line through a series-dropping resistor R6. Terminal 4 of the ZVS provides trigger-pulses to the gate of the load-switching triac in response to an appropriate control signal at terminal 9.



92CM-29961

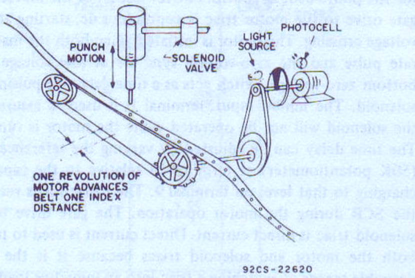
Fig. 41 – Thermocouple temperature control with zero-voltage switching.

The CA3130 is an ideal choice for the type of comparator circuit shown in Fig. 41 because it can "compare" low voltages (such as those generated by a thermocouple) in the proximity of the negative supply rail. Adjustment of potentiometer R1 drives the voltage-divider network R3, R4 so that reference voltages over the range of 0 to 20 millivolts can be applied to noninverting terminal 3 of the comparator. Whenever the voltage developed by the thermocouple at terminal 2 is more positive than the reference voltage applied at terminal 3, the comparator output is toggled so as to sink current from terminal 9 of the ZVS; gate pulses are then no longer applied to the triac. As shown in Fig. 41, the circuit is provided with a control-point "hysteresis" of 1.25 millivolts.

Nulling of the comparator is performed by means of the following procedure: Set R1 at the low end of its range and short the thermocouple output signal appropriately. If the triac is in the conductive mode under these conditions, adjust nulling potentiometer R5 to the point at which triac conduction is interrupted. On the other hand, if the triac is in the nonconductive mode under the conditions above, adjust R5 to the point at which triac conduction commences. The thermocouple output signal should then be unshorted, and R1 can be set to the voltage threshold desired for control-circuit operation.

MACHINE CONTROL AND AUTOMATION

The earlier section on interfacing techniques indicated several techniques of controlling ac loads through a logic system. Many types of automatic equipment are not complex enough or large enough to justify the cost of a flexible logic system. A special circuit, designed only to meet the control requirements of a particular machine, may prove more economical. For example, consider the simple machine shown in Fig. 42; for each revolution of the motor, the belt is advanced a prescribed distance, and the strip is then punched. The machine also has variable speed capability.



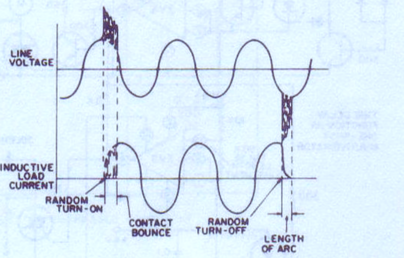
92CS-22620

Fig. 42 – Step-and-punch machine.

The typical electromechanical control circuit for such a machine might consist of a mechanical cambank driven by a separate variable speed motor, a time delay relay, and a few logic and power relays. Assuming use of industrial-grade controls, the control system could get quite costly and large. Of greater importance is the necessity to eliminate transients generated each time a relay or switch energizes and deenergizes the solenoid and motor. Fig. 43 shows such transients, which might not affect the operation of this machine, but could affect the more sensitive solid-state equipment operating in the area.

A more desirable system would use triacs and zero-voltage switching to incorporate the following advantages:

a. Increased reliability and long life inherent in solid-state devices as opposed to moving parts and contacts associated with relays.



92CS-22621

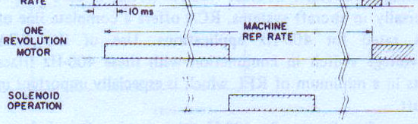
Fig. 43 – Transients generated by relay-contact bounce and non-zero turn-off of inductive load.

b. Minimized generation of EMI/RFI using zero-voltage switching techniques in conjunction with thyristors.

c. Elimination of high-voltage transients generated by relay-contact bounce and contacts breaking inductive loads, as shown in Fig. 42.

d. Compactness of the control system.

The entire control system could be on one printed-circuit board, and an over-all cost advantage would be achieved. Fig. 44 is a timing diagram for the proposed solid-state



92CS-22622

Fig. 44 – Timing diagram for proposed solid-state machine control.

machine control, and Fig. 45 is the corresponding control schematic. A variable-speed machine repetition rate pulse is set up using either a unijunction oscillator or a transistor astable multivibrator in conjunction with a 10-millisecond one-shot multivibrator. The first zero-voltage switch in Fig. 45 is used to synchronize the entire system to zero-voltage crossing. Its output is inverted to simplify adaptation to the rest of the circuit. The center zero-voltage switch is used as an interface for the photo-cell, to control one revolution of the motor. The gate drive to the motor triac is continuous dc, starting at zero voltage crossing. The motor is initiated when both the machine rate pulse and the zero-voltage sync are at low voltage. The bottom zero-voltage switch acts as a time-delay for pulsing the solenoid. The inhibit input, terminal 1, is used to assure that the solenoid will not be operated while the motor is running. The time delay can be adjusted by varying the reference level (50K potentiometer) at terminal 13 relative to the capacitor charging to that level on terminal 9. The capacitor is reset by the SCR during the motor operation. The gate drive to the solenoid triac is direct current. Direct current is used to trigger both the motor and solenoid triacs because it is the most desirable means of switching a triac into an inductive load. The output of the zero-voltage switch will be continuous dc by connecting terminal 12 to common. The output under dc operation should be limited to 20 milliamperes. The motor triac is synchronized to zero crossing because it is a high-crurent inductive load and there is a chance of generating RFI. The solenoid is a very low current inductive load, so there would be little chance of generating RFI: therefore, the initial triac turn-on can be random, which simplifies the circuitry.

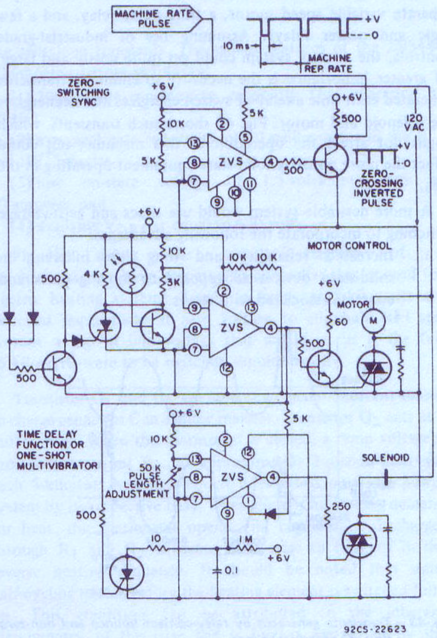


Fig. 45 – Schematic of proposed solid-state machine control.

This example shows the versatility and advantages of the RCA zero-voltage switch used in conjunction with triacs as interfacing and control elements for machine control.

400-Hz TRIAC APPLICATIONS

The increased complexity of aircraft control systems, and the need for greater reliability than electromechanical switching can offer, has led to the use of solid-state power switching in aircraft. Because 400-Hz power is used almost universally in aircraft systems, RCA offers a complete line of triacs rated for 400-Hz applications. Use of the RCA zero-voltage switch in conjunction with these 400-Hz triacs results in a minimum of RFI, which is especially important in aircraft.

Areas of application for 400-Hz triacs in aircraft include:

a. Heater controls for food-warming ovens and for windshield defrosters.
b. Lighting controls for instrument panels and cabin illumination
c. Motor controls
d. Solenoid controls
e. Power-supply switches

Lamp dimming is a simple triac application that demonstrates an advantage of 400-Hz power over 60-Hz power. Fig. 46 shows the adjustment of lamp intensity by phase control of the 60-Hz line voltage. RFI is generated by the step functions of power each half cycle, requiring extensive filtering. Fig. 47 shows a means of controlling power to the lamp by the zero-voltage-switching technique. Use of 400-Hz power makes possible the elimination of complete or half cycles within a period (typically 17.5 milliseconds) without noticeable flicker. Fourteen different levels of lamp intensity can be obtained in this manner. A line-synced ramp is set up with the desired period and applied to terminal No. 9 of the differential amplifier within the zero-voltage switch, as shown in Fig. 48. The other side of the differential amplifier (terminal No. 13) uses a variable reference level, set by the 50K potentiometer. A change of the potentiometer setting changes the lamp intensity.

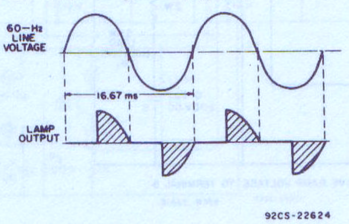


Fig. 46 – Waveforms for 60-Hz phase-controlled lamp dimmer.

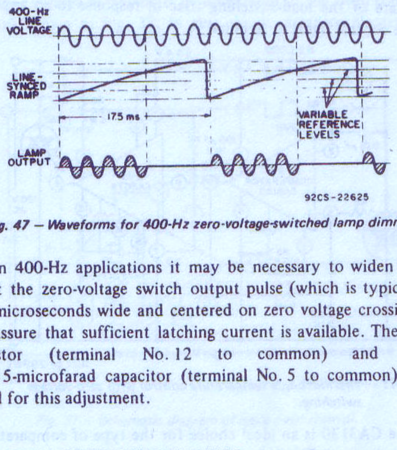


Fig. 47 – Waveforms for 400-Hz zero-voltage-switched lamp dimmer.

In 400-Hz applications it may be necessary to widen and shift the zero-voltage switch output pulse (which is typically 12 microseconds wide and centered on zero voltage crossing), to assure that sufficient latching current is available. The 4K resistor (terminal No. 12 to common) and the 0.015-microfarad capacitor (terminal No. 5 to common) are used for this adjustment.

SOLID-STATE TRAFFIC FLASHER

Another application which illustrates the versatility of the zero-voltage switch, when used with RCA thyristors, involves switching traffic-control lamps. In this type of application, it is essential that a triac withstand a current surge of the lamp load on a continuous basis. This surge results from the difference between the cold and hot resistance of the tungsten filament. If it is assumed that triac turn-on is at 90 degrees from the zero-voltage crossing, the first current-surge peak is approximately ten times the peak steady-state value or fifteen times the steady-state rms value. The second current-surge peak is approximately four times the steady-state rms value.

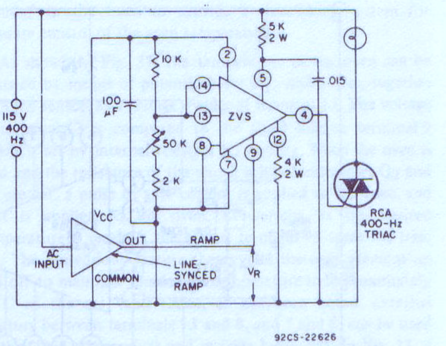
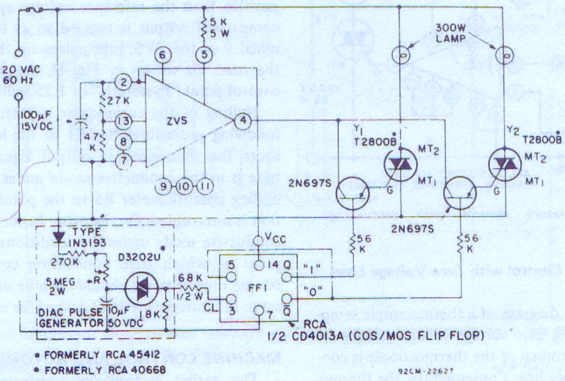


Fig. 48 – Circuit diagram for 400-Hz zero-voltage-switched lamp dimmer.

When the triac randomly switches the lamp, the rate of current rise di/dt is limited only by the source inductance. The triac di/dt rating may be exceeded in some power systems. In many cases, exceeding the rating results in excessive current concentrations in a small area of the device which may produce a hot spot and lead to device failure. Critical applications of this nature require adequate drive to the triac gate for fast turn-on. In this case, some inductance may be required in the load circuit to reduce the initial magnitude of the load current when the triac is passing through the active region. Another method may be used which involves the switching of the triac at zero line voltage. This method involves the supply of pulses to the triac gate only during the presence of zero voltage on the ac line.

Fig. 49 shows a circuit in which the lamp loads are switched at zero line voltage. This approach reduces the initial di/dt, decreases the required triac surge-current ratings, increases the operating lamp life, and eliminates RFI problems. This circuit consists of two triacs, a flip-flop (FF-1), the zero-voltage switch, and a diac pulse generator. The flashing rate in this circuit is controlled by potentiometer R, which provides between 10 and 120 flashes per minute. The state of FF-1 determines the triggering of triacs Y_1 or Y_2 by the output pulses at terminal 4 generated by the zero-crossing circuit. Transistors Q_1 and Q_2 inhibit these pulses to the gates of the triacs until the triacs turn on by the logical "1" (V_{CC} high) state of the flip-flop.

The arrangement described can also be used for a synchronous, sequential traffic-controller system by addition of one triac, one gating transistor, a "divide-by-three" logic circuit, and modification in the design of the diac pulse generator. Such a system can control the familiar red, amber, and green traffic signals that are found at many intersections.



• FORMERLY RCA 45412
• FORMERLY RCA 40668

Fig. 49 – Synchronous-switching traffic flasher.

SYNCHRONOUS LIGHT FLASHER

Fig. 50 shows a simplified version of the synchronous-switching traffic light flasher shown in Fig. 49.

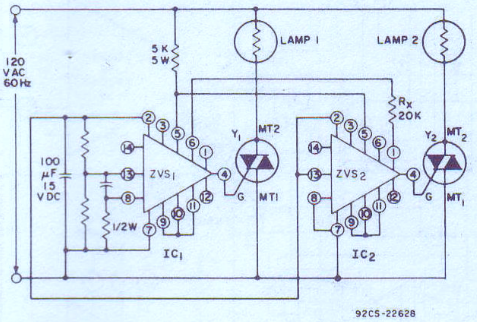


Fig. 50 – Synchronous light flasher.

Flash rate is set by use of the curve shown in Fig. 16. If a more precise flash rate is required, the ramp generator described previously may be used. In this circuit, ZVS_1 is the master control unit and ZVS_2 is slaved to the output of ZVS_1 through its inhibit terminal (terminal 1). When power is applied to lamp No. 1, terminal 6 on ZVS_1 is high and ZVS_2 is inhibited by the current in R_x. When lamp No. 1 is off, ZVS_2 is not inhibited, and triac Y_2 can fire. The power supplies operate in parallel. The on-off sensing amplifier in ZVS_2 is not used.

TRANSIENT-FREE SWITCH CONTROLLERS

The zero-voltage switch can be used as a simple solid-state switching device that permits ac currents to be turned on or off with a minimum of electrical transients and circuit noise.

The circuit shown in Fig. 51 is connected so that, after the control terminal 14 is opened, the electronic logic waits until the power-line voltage reaches a zero crossing before power is applied to the load Z_L. Conversely, when the control terminals are shorted, the load current continues until it reaches a zero crossing. This circuit can switch a load at zero current whether it is resistive or inductive.

The circuit shown in Fig. 52 is connected to provide the opposite control logic to that of the circuit shown in Fig. 51. That is, when the switch is closed, power is supplied to the load, and when the switch is opened, power is removed from the load.

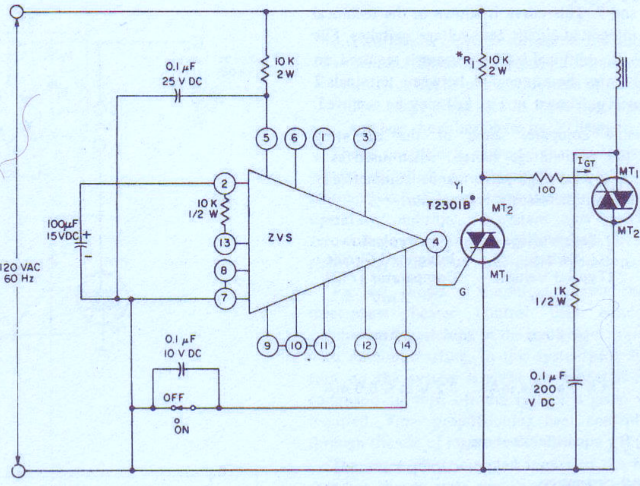
In both configurations, the maximum rms load current that can be switched depends on the rating of triac Y_2. If Y_2 is an RCA-2N5444 triac, an rms current of 40 amperes can be switched.

DIFFERENTIAL COMPARATOR FOR INDUSTRIAL USE

Differential comparators have found widespread use as limit detectors which compare two analog input signals and provide a go/no-go, logic 'one" or logic "zero" output, depending upon the relative magnitudes of these signals. Because the signals are often at very low voltage levels and very accurate discrimination is normally required between them, differential comparators in many cases employ differential amplifiers as a basic building block. However, in many industrial control applications, a high-performance differential comparator is not required. That is, high resolution, fast switching speed, and similar features are not essential. The zero-voltage switch is ideally suited for use in such applications. Connection of terminal 12 to terminal 7 inhibits the zero-voltage threshold detector of the zero-voltage switch, and the circuit becomes a differential comparator.

Fig. 53 shows the circuit arrangement for use of the zero-voltage switch as a differential comparator. In this application, no external dc supply is required, as is the case with most commercially available integrated-circuit comparators; of course, the output-current capability of the zero-voltage switch is reduced because the circuit is operating in the dc mode. The 1000-ohm resistor R_G, connected between terminal 4 and the gate of the triac, limits the output current to approximately 3 milliamperes.

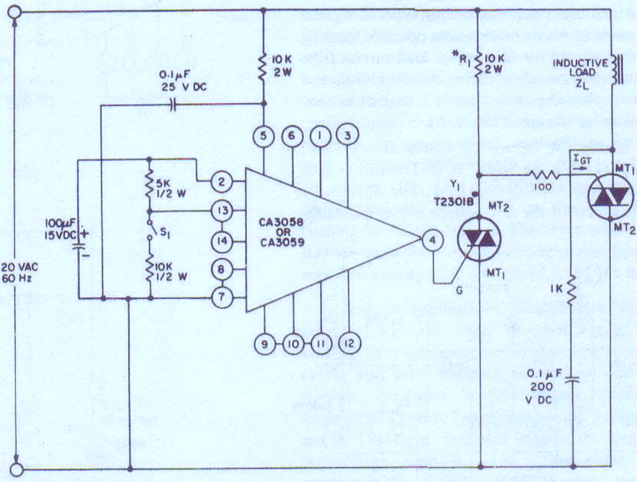
When the zero-voltage switch is connected in the dc mode, the drive current for terminal 4 can be determined from a curve of the external load current as a function of dc voltage



*IF Y_2, FOR EXAMPLE, IS A 40-AMPERE TRIAC, THEN R_1 MUST BE DECREASED TO SUPPLY SUFFICIENT I_{GT} FOR Y_2.

• FORMERLY RCA 40691

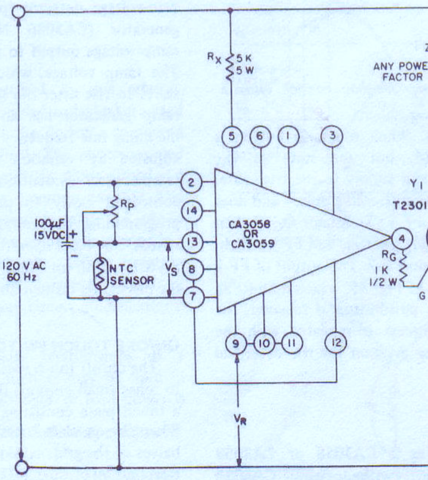
Fig. 51 – Zero-voltage switch transient-free switch controller in which power is supplied to the load when the switch is open.



*IF Y_2, FOR EXAMPLE, IS A 40-AMPERE TRIAC, R_1 MUST BE DECREASED TO SUPPLY SUFFICIENT I_{GT} FOR Y_2

• FORMERLY RCA 40691

Fig. 52 – Zero-voltage switch transient-free switch controller in which power is applied to the load when the switch is closed.



• FORMERLY RCA 40691

Fig. 53 – Differential comparator using the CA3058 or CA3059 integrated-circuit zero-voltage switch.

from terminals 2 and 7. This curve is shown in the technical bulletin for RCA integrated-circuit zero-voltage switches, File No. 490. Of course, if additional output current is required, an external dc supply may be connected between terminals 2 and 7, and resistor R_X (shown in Fig. 53) may be removed.

The chart below compares some of the operating characteristics of the zero-voltage switch, when used as a comparator, with a typical high-performance commercially available integrated-circuit differential comparator.

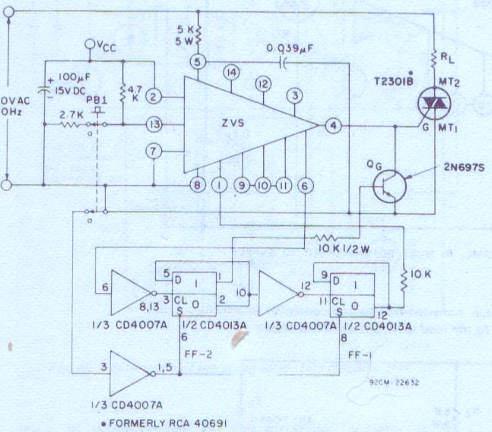
Parameters	Zero-Voltage Switch (Typical Values)	Typical Integrated-Circuit Comparator (710)
Sensitivity	30 mV	2 mV
Switching speed (rise time)	> 20 μs	90 ns
Output drive capability	*4.5 V at ≤ 4 mA	3.2 V at ≤ 5.0 mA

* Refer to Fig. 20; R_X equals 5000 ohms.

POWER ONE-SHOT CONTROL

Fig. 54 shows a circuit which triggers a triac for one complete half-cycle of either the positive or negative alternation of the ac line voltage. In this circuit, triggering is initiated by the push button PB-1, which produces triggering of the triac near zero voltage even though the button is randomly depressed during the ac cycle. The triac does not trigger again until the button is released and again depressed. This type of logic is required for the solenoid drive of electrically operated stapling guns, impulse hammers, and the like, where load-current flow is required for only one complete half-cycle. Such logic can also be adapted to keyboard consoles in which contact bounce produces transmission of erroneous information.

In the circuit of Fig. 54, before the button is depressed, both flip-flop outputs are in the "zero" state. Transistor Q_G is biased on by the output of flip-flop FF-1. The differential comparator which is part of the zero-voltage switch is initially biased to inhibit output pulses. When the push button is depressed, pulses are generated, but the state of Q_G determines the requirement for their supply to the triac gate. The first pulse generated serves as a "framing pulse" and does not trigger the triac but toggles FF-1. Transistor Q_G is then turned off. The second pulse triggers the triac and FF-1 which, in turn, toggles the second flip-flop FF-2. The output of FF-2 turns on transistor Q_7, as shown in Fig. 55, which inhibits all further output pulses. When the pushbutton is released, the circuit resets itself until the process is repeated with the button. Fig. 56 shows the timing diagram for the described operating sequence.



• FORMERLY RCA 40691

Fig. 54 – Block diagram of a power one-shot control using a zero-voltage switch.

PHASE CONTROL CIRCUIT

Fig. 57 shows a circuit using a CA3058 or CA3059 zero-voltage switch together with two CA3086 integrated-circuit transistor arrays to form a phase-control circuit. This circuit is specifically designed for speed control of ac induction motors, but may also be used as a light dimmer.

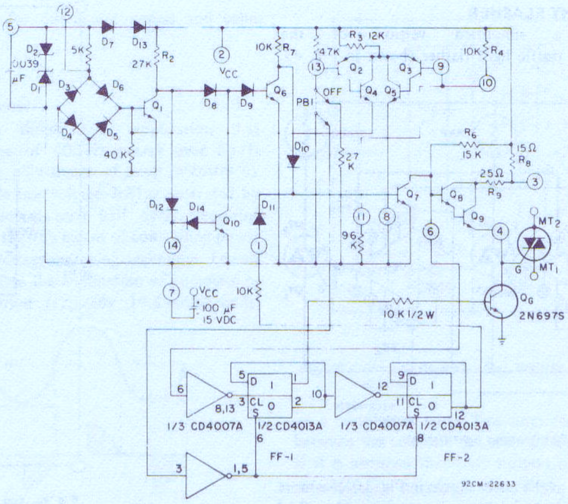


Fig. 55 – Circuit diagram for the power one-shot control.

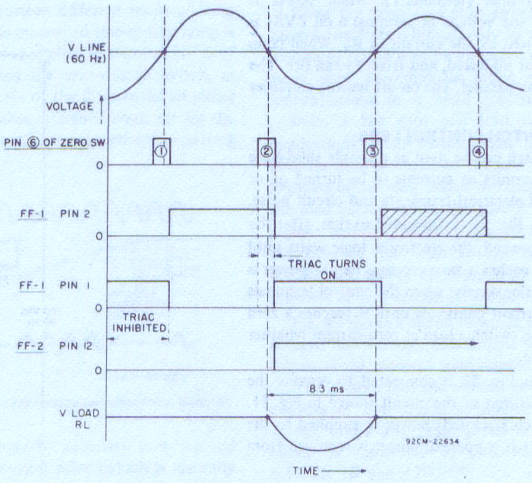


Fig. 56 – Timing diagram for the power one-shot control.

The circuit, which can be operated from a line frequency of 50-Hz to 400-Hz, consists of a zero-voltage detector, a line-synchronized ramp generator, a zero-current detector, and a line-derived control circuit (i.e., the zero-voltage switch). The zero-voltage detector (part of CA3086 No. 1) and the ramp generator (CA3086 No. 2) provide a line-synchronized ramp-voltage output to terminal 13 of the zero-voltage switch. The ramp voltage, which has a starting voltage of 1.8 volts, starts to rise after the line voltage passes the zero point. The ramp generator has an oscillation frequency of twice the incoming line frequency. The slope of the ramp voltage can be adjusted by variation of the resistance of the 1-megohm ramp-control potentiometer. The output phase can be controlled easily to provide 180° firing of the triac by programming the voltage at terminal 9 of the zero-voltage switch. The basic operation of the zero-voltage switch driving a thyristor with an inductive load was explained previously in the discussion on switching of inductive loads.

ON/OFF TOUCH SWITCH

The on/off touch switch shown in Fig. 58 uses the CA3240E to sense small currents flowing between two contact points on a touch plate consisting of a PC board metallization "grid". When the on plate is touched, current flows between the two halves of the grid, causing a positive shift in the output voltage (terminal 7) of the CA3240E. These positive transitions are fed into the CA3059, which is used as a latching circuit and zero-crossing triac driver. When a positive pulse occurs at terminal No. 7 of the CA3240E, the triac is turned on and held on by the CA3059 and associated positive feedback circuitry (51-kilohm resistor and 36-kilohm/42-kilohm voltage divider). When the pulse occurs at terminal No. 1, the triac is turned off and held off in a similar manner. Note that power for the CA3240E is derived from the CA3059 internal power supply. The advantage of using the CA3240E in this circuit is that it can sense the small currents associated with skin conduction while maintaining sufficiently high circuit impedance to protect against electrical shock.

TRIAC POWER CONTROLS FOR THREE-PHASE SYSTEMS

This section describes recommended configurations for power-control circuits intended for use with both inductive and resistive balanced three-phase loads. The specific design requirements for each type of loading condition are discussed.

In the power-control circuits described, the integrated-circuit zero-voltage switch is used as the trigger circuit for the power triacs. The following conditions are also imposed in the design of the triac control circuits:

1. The load should be connected in a three-wire configuration with the triacs placed external to the load; eiter delta or wye arrangements may be used. Four-wire loads in wye configurations can be handled as three independent single-phase systems. Delta configurations in which a triac is connected within each phase rather than in the incoming lines can also be handled as three independent single-phase systems.
2. Only one logic command signal is available for the

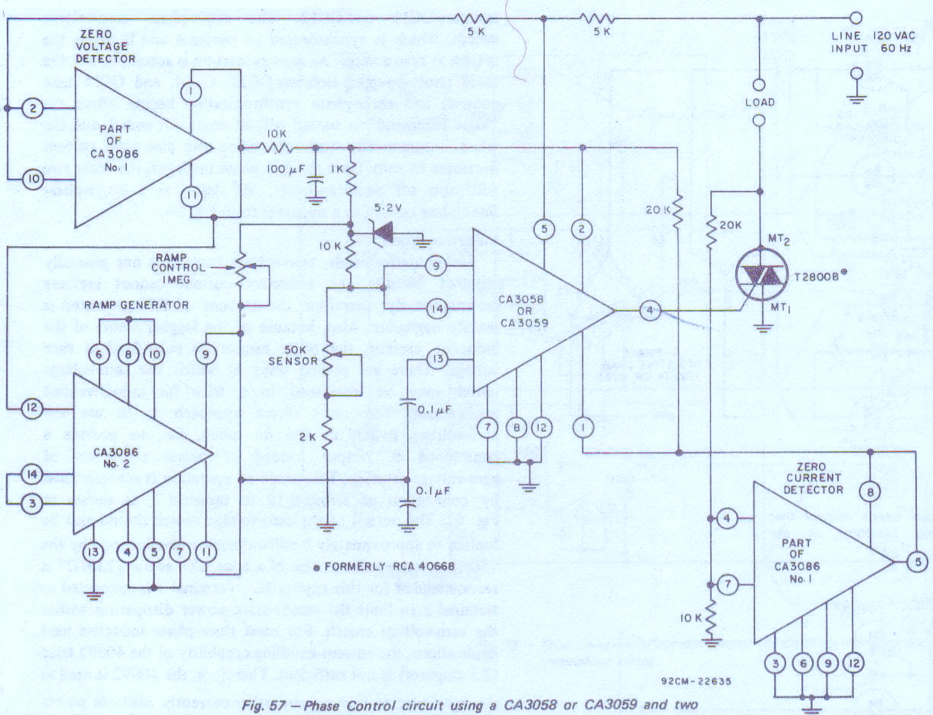


Fig. 57 – Phase Control circuit using a CA3058 or CA3059 and two CA3086 integrated-circuits.

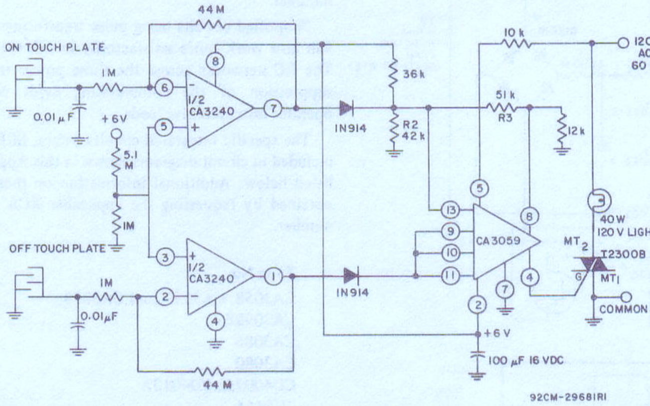


Fig. 58 – On-off touch switch.

control circuits. This signal must be electrically isolated from the three-phase power system.

3. Three separate triac gating signals are required.
4. For operation with resistive loads, the zero-voltage switching technique should be used to minimize any radio-frequency interference (RFI) that may be generated.

Isolation of DC Logic Circuitry

As explained earlier under **Special Application Considerations**, isolation of the dc logic circuitry* from the ac line, the triac, and the load circuit is often desirable even in many single-phase power-control applications. In control circuits for polyphase power systems, however, this type of isolation is essential, because the common point of the dc logic circuitry cannot be referenced to a common line in all phases.

In the three-phase circuits described in this section, photo-optic techniques (i.e., photo-coupled isolators) are used to provide the electrical isolation of the dc logic command signal from the ac circuits and the load. The photo-coupled isolators consist of an infrared light-emitting diode aimed at a silicon photo transistor, coupled in a common package. The light-emitting diode is the input section, and the photo transistor is the output section. The two components provide a voltage isolation typically of 1500 volts. Other isolation techniques, such as pulse transformers, magnetoresistors, or reed relays, can also be used with some circuit modifications.

Resistive Loads

Fig. 59 illustrates the basic phase relationships of a balanced three-phase resistive load, such as may be used in heater applications, in which the application of load power is controlled by zero-voltage switching. The following conditions are inherent in this type of application:

1. The phases are 120 degrees apart; consequently, all three phases cannot be switched on simultaneously at zero voltage.
2. A single phase of a wye configuration type of three-wire system cannot be turned on.
3. Two phases must be turned on for initial starting of the system. These two phases form a single-phase circuit which is out of phase with both of its component phases. The single-phase circuit leads one phase by 30 degrees and lags the other phase by 30 degrees.

These conditions indicate that in order to maintain a system in which no appreciable RFI is generated by the switching action from initial starting through the steady-state operating condition, the system must first be turned on, by zero-voltage switching, as a single-phase circuit and then must revert to synchronous three-phase operation.

Fig. 60 shows a simplified circuit configuration of a three-phase heater control that employs zero-voltage synchronous switching in the steady-state operating condition, with random starting. In this system, the logic command to turn on the system is given when heat is required, and the command to turn off the system is given when heat is not required. Time proportioning heat control is also possible through the use of logic commands.

The three photo-coupled inputs to the three zero-voltage switches change state simultaneously in response to a "logic command". The zero-voltage switches then provide a positive pulse, approximately 100 microseconds in duration, only at a zero-voltage crossing relative to their particular phase. A balanced three-phase sensing circuit is set up with the three zero-voltage switches each connected to a particular phase on their common side (terminal 7) and referenced at their high side (terminal 5), through the current-limiting resistors R4, R5, and R6, to an established artificial neutral point. This artificial neutral point is electrically equivalent to the inaccessible neutral point of the wye type of three-wire load and, therefore, is used to establish the desired phase relationships. The same artificial neutral point is also used to establish the proper phase relationships for a delta type of three-wire load. Because only one triac is pulsed on at a time, the diodes (D1, D2, and D3) are necessary to trigger the opposite-polarity triac, and, in this way, to assure initial latching-on of the system. The three resistors (R1, R2, and R3) are used for current limiting of the gate drive when the opposite-polarity triac is triggered on by the line voltage.

In critical applications that require suppression of all generated RFI, the circuit shown in Fig. 61 may be used. In addition to synchronous steady-state operating conditions, this circuit also incorporates a zero-voltage starting circuit. The start-up condition is zero-voltage synchronized to a single-phase, 2-wire, line-to-line circuit, comprised of phases A and B. The logic command engages the single-phase start-up zero-voltage switch and three-phase photo-coupled isolators OC13, OC14, OC15 through the photo-coupled

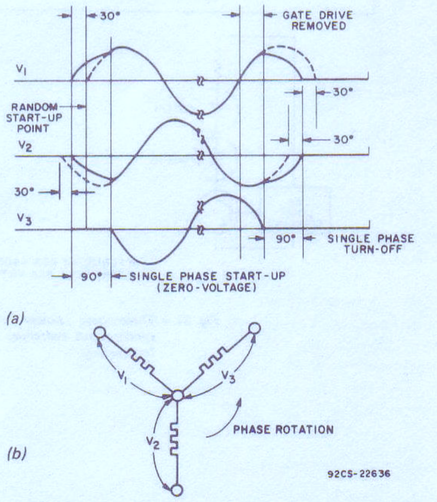


Fig. 59 – Voltage phase relationship for a three-phase resistive load when the application of load power is controlled by zero-voltage switching: (a) voltage waveforms, (b) load-circuit orientation of voltages. (The dashed lines indicate the normal relationship of the phases under steady-state conditions. The deviation at start-up and turn-off should be noted.)

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* The dc logic circuitry provides the low-level electrical signal that dictates the state of the load. For temperature controls, the dc logic circuitry includes a temperature sensor for feedback. The RCA integrated-circuit zero-voltage switch, when operated in the dc mode with some additional circuitry, can replace the dc logic circuitry for temperature controls.

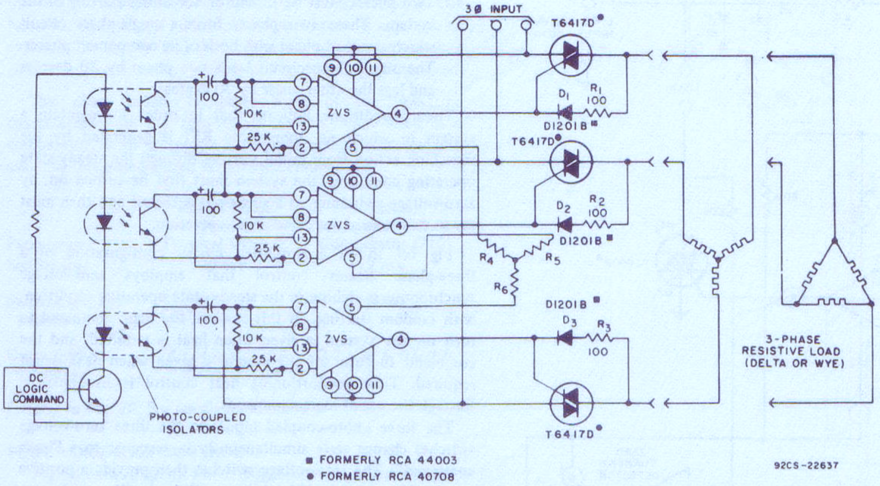

Fig. 60 – Simplified diagram of a three-phase heater control that employs zero-voltage synchronous switching in the steady-state operating conditions.

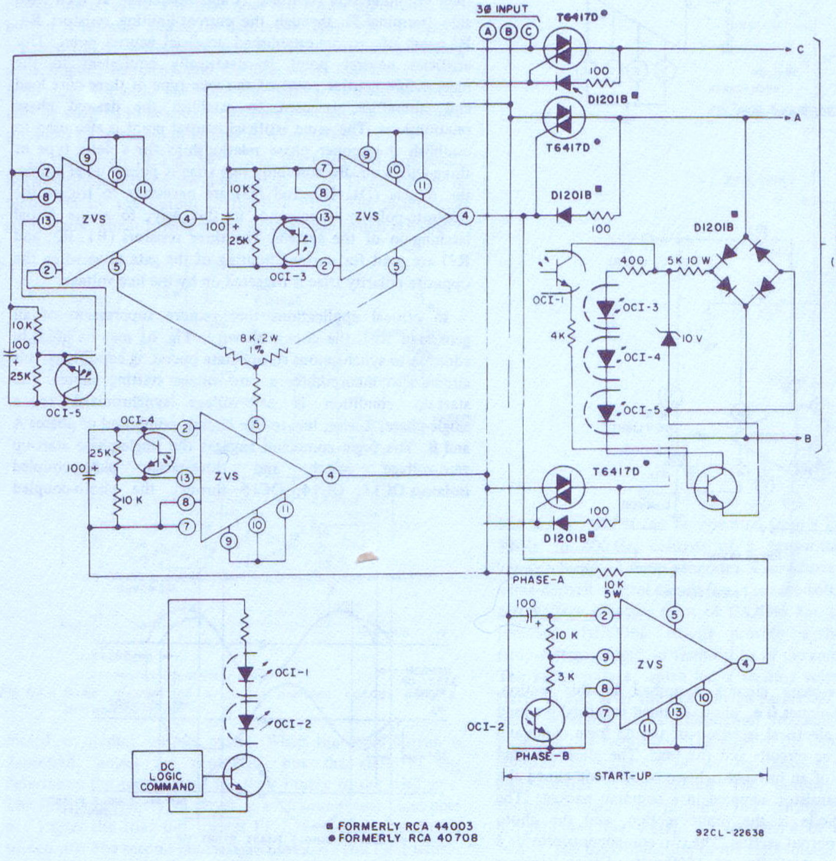

Fig. 61 – Three-phase power control that employs zero-voltage synchronous switching both for steady-state operation and for starting.

isolators OC11 and OC12. The single-phase zero-voltage switch, which is synchronized to phases A and B, starts the system at zero voltage. As soon as start-up is accomplished, the three photo-coupled isolators OC13, OC14, and OC15 take control, and three-phase synchronization begins. When the "logic command" is turned off, all control is ended, and the triacs automatically turn off when the sine-wave current decreases to zero. Once the first phase turns off, the other two will turn off simultaneously, 90° later, as a single-phase line-to-line circuit, as is apparent from Fig. 59.

Inductive Loads

For inductive loads, zero-voltage turn-on is not generally required because the inductive current cannot increase instantaneously; therefore, the amount of RFI generated is usually negligible. Also, because of the lagging nature of the inductive current, the triacs cannot be pulse-fired at zero voltage. There are several ways in which the zero-voltage switch may be interfaced to a triac for inductive-load applications. The most direct approach is to use the zero-voltage switch in the dc mode, i.e., to provide a continuous dc output instead of pulses at points of zero-voltage crossing. This mode of operation is accomplished by connection of terminal 12 to terminal 7, as shown in Fig. 62. The output of the zero-voltage switch should also be limited to approximately 5 milliamperes in the dc mode by the 750-ohm series resistor. Use of a triac such as the T2301D* is recommended for this application. Terminal 3 is connected to terminal 2 to limit the steady-state power dissipation within the zero-voltage switch. For most three-phase inductive load applications, the current-handling capability of the 40692 triac (2.5 amperes) is not sufficient. Therefore, the 40692 is used as a trigger triac to turn on any other currently available power triac that may be used. The trigger triac is used only to provide trigger pulses to the gate of the power triac (one pulse per half cycle); the power dissipation in this device, therefore, will be minimal.

Simplified circuits using pulse transformers and reed relays will also work quite satisfactorily in this type of application. The RC networks across the three power triacs are used for suppression of the commutating dv/dt when the circuit operates into inductive loads.

The specific integrated-circuits, triacs, SCR's, and rectifiers included in circuit diagrams shown in this Application Note are listed below. Additional information on these devices can be obtained by requesting the applicable RCA data-bulletin file number.

Type No.	File No.
CA3058, CA3059, and CA3079	490
CA3099E	620
CA3086	483
CA3080	475
CD4007A, CD4013A	479
2N5444	456
T2800B (40668)	364
T2300B (40526)	470
T2301B (40691), T2301D (40692)	431
T6417O (40708)	406
S2600D (40655)	496
D1201B (44003)	495
D3202U (45412)	577

Note: Numbers in parenthesis (e.g. 40668) are former RCA type numbers.

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* Formerly RCA 40692

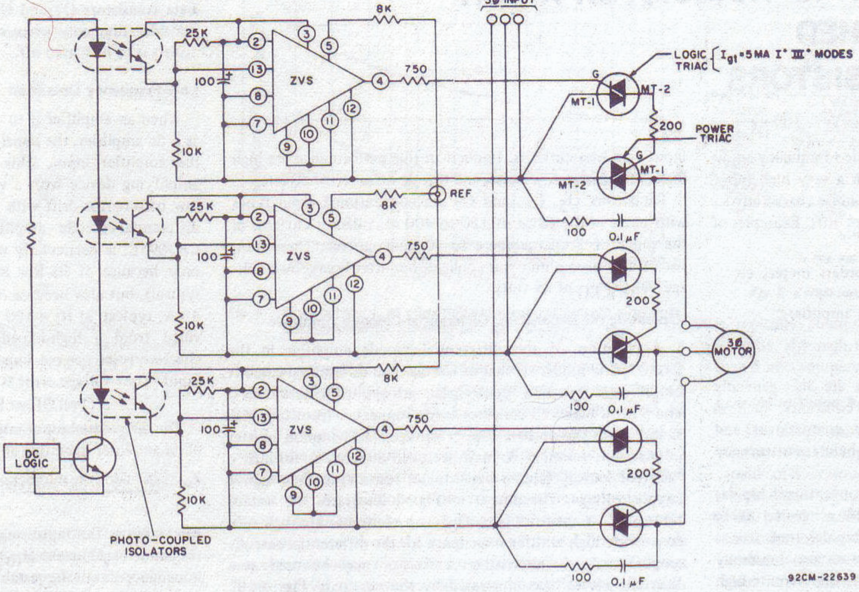

Fig. 62 – Triac three-phase control circuit for an inductive load, i.e., three-phase motor.