Unit 56 SCRs and triacs for power control

- A silicon controlled rectifier (SCR) can be triggered into conduction in the forward direction by application of a pulse to the gate terminal of the SCR.
- A triac can be triggered into conduction in either direction by application of a pulse to the gate terminal.
- A unijunction transistor (UJT) is used in a relaxation oscillator to give a train of trigger pulses for SCRs and triacs.
- A diac (bidirectional diode thyristor) conducts when the threshold voltage of about 20 V is exceeded. Once triggered, the device resistance then drops rapidly.
- In phase angle triggering of triacs, a variable segment of each half waveform of current is passed through the load.
- In burst fire control, the full power is applied to the load for a variable fraction of the time to get the required average power dissipation. The ON time corresponds to an integral number of half cycles of current.

When a transistor is used to control the current through a load, the full voltage of the power supply is applied across the transistor and load in series to give $V_S = V_T + V_L$. The same current, I, flows in both the transistor and the load so the power dissipated in the transistor is $I \times V_T$ and the power dissipated in the load is $I \times V_L$. This is not important for small currents because a simple heat sink is sufficient to dissipate the heat from the transistor but for large currents of the order of amps and for voltages of the order of hundreds of volts the power dissipated in the transistor is usually too great to be readily dissipated and heat damage to the transistor usually results.

If the system is of necessity linear, such as in the case of high power audio amplifiers, radio transmitters etc., then the older technology of thermionic valves may have to be utilized. However, if the requirement is that the average power or current in the load be controlled then rapidly switching the full current on and off to get an average current somewhere between the minimum and maximum can be very effective. There is therefore a need for an electronic switch which can turn current on and off very rapidly without switch wear and which can be used for controlling large currents.

No power is dissipated in an ideal switch because when the switch is open $P = V \times I = V \times 0 = 0$ since there is no current and when the switch is closed again $P = V \times I = 0 \times I = 0$ because the closed switch has zero resistance and there is no voltage drop across the switch.

One problem with switches is that they are mechanical and slow, typically taking a fifth of a second to operate. But a more significant problem is that each time a switch operates, there is an arc or spark at the contacts which leads to erosion of the metal and in extreme cases welding together of the contacts. One example of contact wear is the need to replace the points in a car ignition system every 15,000 km or sooner because of wear of the contact metal. In the car, the function of the points is to interrupt the current in the primary of the high tension coil or transformer which generates the spark for ignition of the petrol.

In principle a transistor can be switched or driven rapidly from the non-conducting state to the conducting state and made to spend a very short time in the high power dissipation zone, but the necessary circuitry is complex. A more efficient approach is to use a latch circuit in which positive feedback is employed to give very rapid switching.

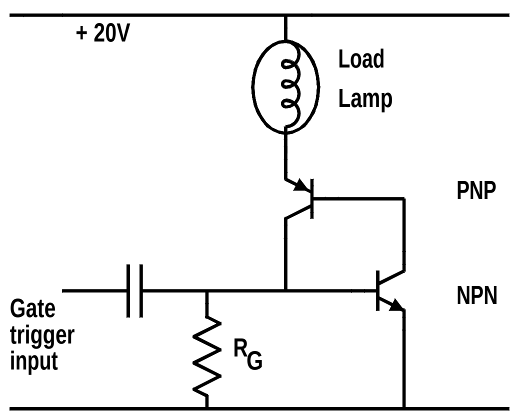

Figure 56.1: A two transistor latch circuit.

Figure 56.1 shows a two transistor latch circuit. When the supply voltage is turned on, there is no current in either transistor and therefore there is no current in the lamp which is the load in this example. The lamp could be replaced by a motor or a heater but a filament bulb is very convenient for experiments in the laboratory and also for testing circuits in the field.

The circuit operates as follows. With the latch in the OFF state, the R_G resistor, typically 10 kΩ, holds the base of the npn transistor at the emitter voltage so there is no base current and therefore there is no collector current in the npn transistor. This means that there is no base current for the pnp transistor which means that there is no collector current in the pnp transistor which gives no base current in the npn transistor as we assumed at the beginning. So the circuit configuration is logically consistent with no current in either transistor. (Note the logical argument which is used here and which is often very useful in electronics: make an assumption about the input and trace the effects around the feedback loop back to the input; if the loop back is consistent with the assumption made about the input then that is a stable configuration for the loop.)

Now apply a short positive pulse of about a volt to the input through the capacitor. This causes the npn transistor to become forward biased and the transistor conducts momentarily. The collector current of the npn transistor is the base current of the pnp transistor so the pnp transistor conducts and this gives collector current in the pnp which gives base current in the npn which reinforces the initial trigger pulse from the external source. The current is amplified by a factor of about 10,000 each time the signal propagates round the loop so there is very rapid switching from the OFF state to the ON state for both transistors.

The current continues to grow until it is limited by the resistance, R_L, of the load. The current growth then stops and the circuit enters a stable state with about 1 V across each transistor and both transistors conducting. The latch circuit is then stable in the ON state and will remain in this ON state until the power is switched off.

In principle, a large negative pulse at the trigger input could turn off the latch but in practice it is found that it is difficult to turn off a latch circuit once it has latched on, basically because the turn-off trigger pulse must supply all of the current through the latch for long enough for the latch to stop conducting or 'drop out'. This is therefore one difference with a mechanical light switch which latches equally well to the OFF state as it latches to the ON state. An electronic latch turns on easily but is difficult to turn off.

In Figure 56.2 (a) we show the two transistor latch which we have just discussed. The connections between the npn-pnp transistor layers are shown in Figure 56.2 (b). In Figure 56.2 (c) we have merged the connected layers to get a four layer device which is called an SCR or silicon controlled rectifier or thyristor and for which the conventional circuit diagram symbol is shown in Figure 56.2 (d).

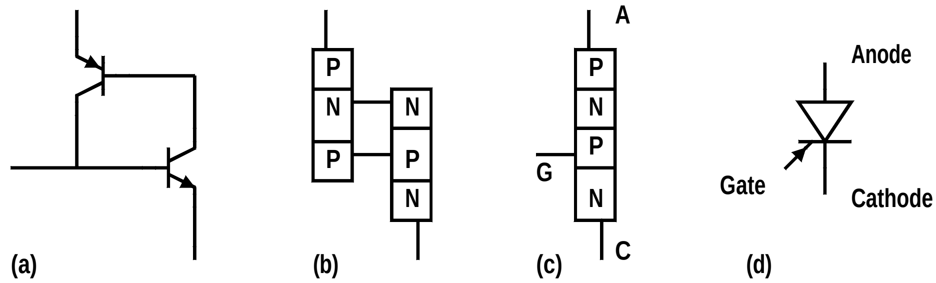

Figure 56.2: Evolution of a latch circuit to an SCR.

The performance of the SCR is exactly the same as that of the two transistor latch which we have discussed except that the device is available with voltage ratings up to 1000 V and current ratings up to a few hundred amps.

In the operation of SCRs there are a few important parameters which must be considered:

- SCR has the word 'rectifier' in its name. Current can only flow through the SCR in the direction of the arrow in the circuit symbol of the diode. Current then only flows when the SCR has been triggered.
- A holding current or minimum current must flow through the SCR in order to maintain it in the conducting state.
- Break over voltage is the maximum voltage which can be applied between the anode and the cathode of the SCR in the forward direction without the SCR going into the conducting state in the absence of a trigger to the gate.
- V_{RRM} is the maximum reverse blocking voltage of the SCR.
- Trigger voltages and currents are typically of the order of 2 V and 20 mA for about 5 μs.
- $\frac{dV}{dt}_{max}$ is the maximum rate of change of the anode voltage which will not cause spurious triggering of the SCR.
- $I_{T\,ave}$ is the maximum average current rating of the SCR.

In general, it is necessary that attention be paid to the maximum ratings of the SCR because the applications are usually at higher voltage and higher current than normal transistor applications and the possibility of serious heat damage to the SCR is that much greater.

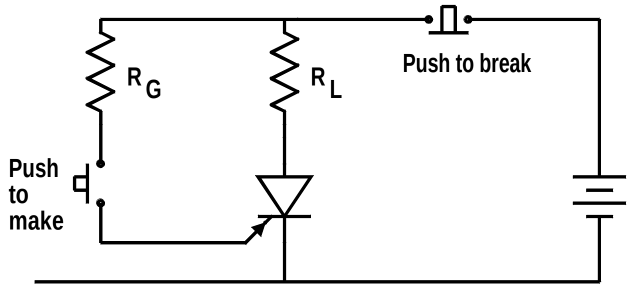

Figure 56.3: DC triggering of an SCR.

We now examine some representative circuits which show the operation of SCRs and demonstrate the basic principles of SCR triggering. The simplest trigger circuit is the DC circuit shown in Figure 56.3 where switches are used to control the small trigger signals to the SCR. The resistor, R_G, limits the gate current to the permissible limit. For instance, if the specified gate current is $I_G = 10\,\mathrm{mA}$ and with a 20 V supply an $R_G = \frac{20}{0.01} = 2\,\mathrm{k}\Omega$ would give reliable triggering when the push to make triggering button is pressed. The load, R_L, could be any load which draws a current less than the maximum average current for the particular SCR, $I_{T\,ave}$.

Some care must be taken when the load is a filament bulb since the current which flows immediately after the bulb is turned on can be up to five times the current which flows when the bulb is hot, owing to the change in the resistance of the filament as it heats up, and therefore you must choose an SCR with the current rating for the higher starting current. If the load is a motor with a commutator then there is the possibility that a momentary interruption of the current due to a bad contact at the commutator can cause the SCR to drop out of conduction.

In the circuit in Figure 56.3 the current can only be turned off by interrupting the current through the SCR by pressing the push to break OFF button so this circuit is really only useful for demonstrating the principle of DC SCR triggering.

It is when the SCR is used in AC circuits that the versatile aspects of SCRs start to become apparent. Figure 56.4 shows an SCR circuit powered from an AC supply. For safety reasons, in laboratory experimental work, you should use an isolating transformer. The circuit will, however, operate satisfactorily and switch mains voltages without the use of any isolation. But you cannot connect oscilloscopes to the mains without extreme care in the use of the ground connection of the oscilloscope test lead so the opportunities for diagnostic exploration are restricted.

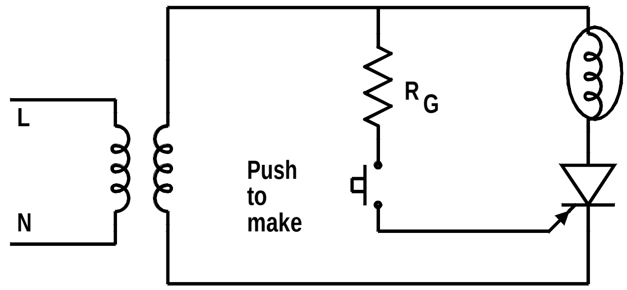

Figure 56.4: Triggering of an SCR in an AC circuit.

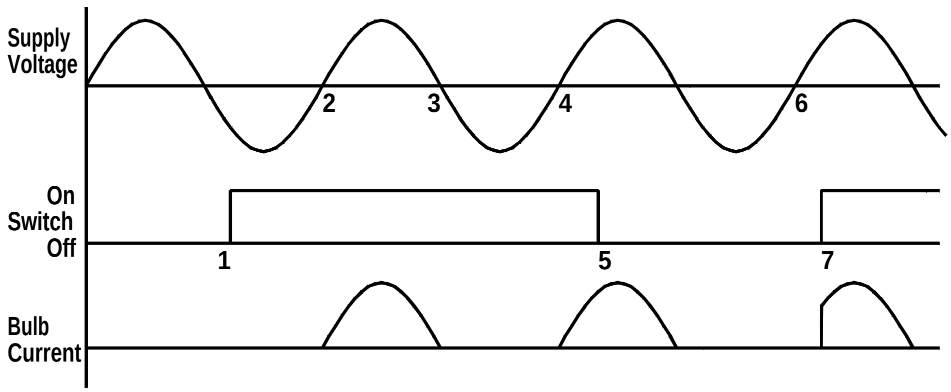

Figure 56.5: V and I waveforms in an AC SCR circuit.

A waveform diagram for this circuit is shown in Figure 56.5 which shows up a number of important features of SCRs when used with AC triggering. The relevant points in the waveforms in Figure 56.5 have been labelled with numbers for the purposes of this discussion.

1. The ON switch is pressed but no current flows because the SCR is reverse biased.

2. The waveform goes positive which gives positive gate current and positive voltage across the SCR so the SCR triggers and current flows in the load as shown in the graph of bulb current, I_{Bulb}.

3. The waveform goes negative and the SCR stops conducting because of the rectifier or diode action of the SCR.

4. The voltage goes positive again and the button is still pressed so the SCR conducts.

5. The trigger button is released but the SCR continues to conduct, because of the latching action of the SCR, until the end of the half cycle when the SCR drops out of conduction.

6. The SCR is OFF because there is no gate trigger.

7. The trigger button is pressed during a positive half cycle and the SCR immediately conducts for the remainder of the half cycle.

Triggering of SCRs by applying DC or AC signal switching to the gate does operate but has one great disadvantage in that there is a wired or galvanic connection between the trigger circuit and the high voltages and currents which are present in the power circuit controlled by the SCR. This can constitute a significant hazard of electrical shock for operators.

In an effort to provide isolation between the sensing and control circuits and the power circuits a device called a unijunction transistor or UJT has been developed. Figure 56.6 (a) shows a schematic diagram of the construction of a UJT.

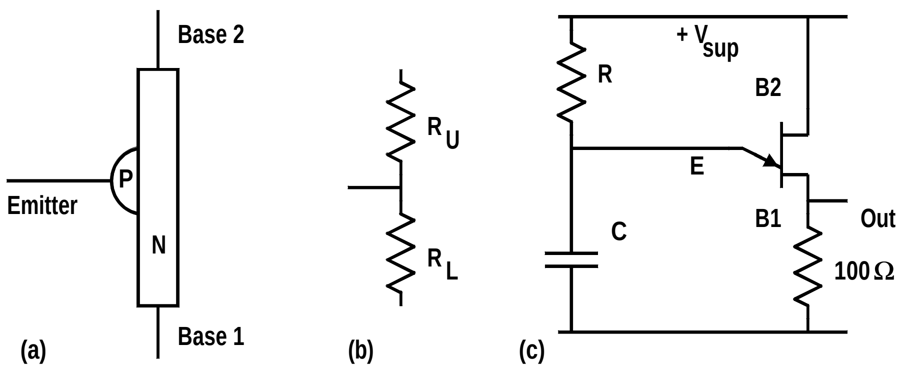

Figure 56.6: Unijunction transistor oscillator circuit.

The device is essentially a long resistor of n-type silicon. The n-type doping concentration is low and therefore the resistance of the resistor is high. At a point about half way along a p-type junction is made to the n-type resistor which gives a point pn junction. When a voltage is applied between base 1 and base 2, the two ends of the resistor, the device behaves just like a potential divider with the voltage at the p-type junction given by the usual potential divider formula. Since $R_U \approx R_L$ initially, the potential at the junction is about half way between zero and the supply voltage. When the external voltage applied to the emitter terminal is less than the voltage set by the effective potential, the pn junction is reverse biased and no current flows through the junction.

However, if the voltage applied at the emitter rises above the voltage at the centre of the bar as set by the potential divider then the pn junction becomes forward biased and p-type holes are injected into the bar from the heavily doped p-type region. These injected holes move down into the lower resistor, R_L, and lower the value of R_L drastically from a typical value of $\approx 50\,\mathrm{k\Omega}$ to a value $\approx 10\,\Omega$.

The device is used in a circuit such as that in Figure 56.6 (c). The capacitor charges exponentially from zero towards the supply voltage and eventually reaches the trigger voltage for the device which is given by ηV_{sup} where $\eta \approx 0.6$ is called the intrinsic stand-off ratio for the UJT. At this point the resistance from the emitter to the base 1 terminal decreases rapidly owing to the injection of holes and the charge on the capacitor flows through the $100\,\Omega$ resistor to discharge the capacitor and to give a very fast (typically $5\,\mu$s) current pulse at the base 1 terminal. When the capacitor discharges, the injection of holes into the lower resistor stops and the resistance, R_L, reverts to its original high value so that the charge-up of the capacitor starts again giving a continuous train of pulses at base 1.

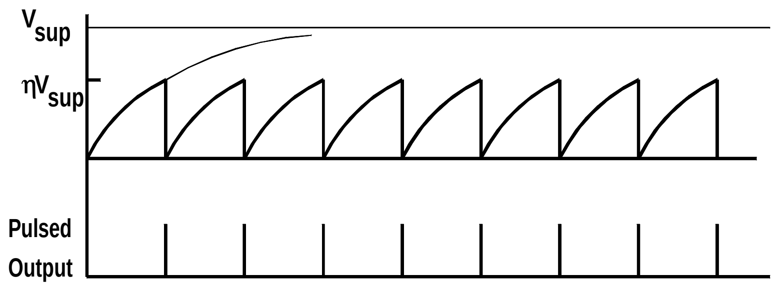

Figure 56.7: Voltage waveforms in a UJT oscillator circuit.

This is shown in Figure 56.7 where the charging of the capacitor towards the supply voltage is shown together with the fast pulses at base 1. If you build this circuit, you will have to adjust the oscilloscope trigger carefully if you are to see these fast pulses clearly.

The period of these pulses is approximately given by $T \approx RC$ with R in the range from $5\,\mathrm{k\Omega}$ to $30\,\mathrm{k\Omega}$ for typical UJTs such as the 2N2646 device.

A typical application of the device is shown in Figure 56.8 where the level of water in a tank is sensed by the float level switch which closes when the tank is full. For a partially empty tank, the level switch is open so the UJT circuit is free to oscillate and deliver a train of pulses at base 1 terminal. A small transformer, called a pulse transformer, is used to couple the UJT pulse to the gate of the SCR. The pulse transformer has very high primary to secondary voltage isolation and is designed for operation with high frequency

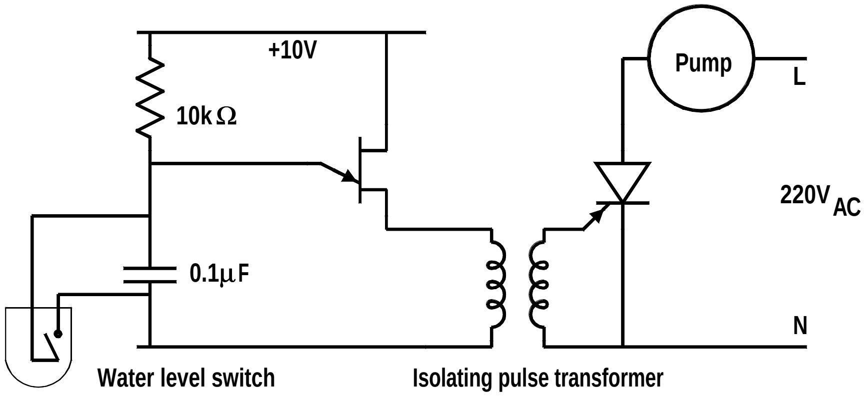

Figure 56.8: Use of UJT oscillator for galvanic isolation.

pulses giving good isolation from electrical shock between the sensing circuit and the power circuit. The function and operation of this transformer is very similar to that of the transformer used in the isolation amplifiers discussed in Unit 51.

The rapid train of pulses at the gate of the SCR triggers the SCR allowing DC to flow through the DC motor in the pump which then fills the tank. When the level in the tank rises to the level switch, the switch closes and shorts out the capacitor of the UJT oscillator, stopping the oscillation and the train of pulses to the SCR. The current in the motor then stops at the next zero crossing of the mains voltage waveform so that the tank does not overfill. If water is drawn off from the tank, the level drops, the switch opens, the UJT oscillator starts again and supplies triggering pulses to the SCR so that water is pumped in again to maintain the level.

The circuit in Figure 56.8 illustrates another point about SCRs. When they are used with mains supplies in control applications, the SCR is usually located on the neutral side of the load heater or motor whereas a normal switch or contactor is usually located in the line from the live of the mains supply. With the SCR on the neutral side, the motor is at mains supply voltage when it is off and there is therefore a great danger of electrical shock for anyone who is not careful!

SCRs allow the control of DC or of rectified AC but do not pass the full AC waveform and so cannot be used with most induction motors.

Full wave control could be achieved by using two SCRs back to back as shown in Figure 56.9 but a better approach is to use a triac which is equivalent to two back to back SCRs with a single gate terminal as shown in Figure 56.9.

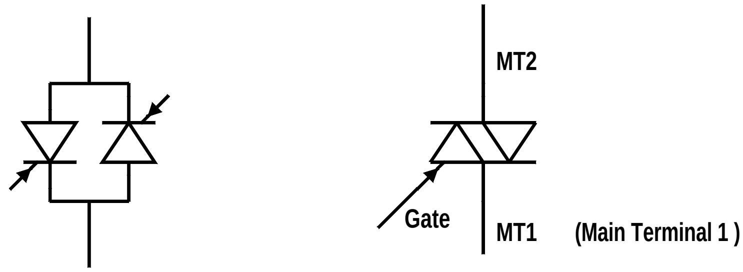

Figure 56.9: Evolution of two SCRs to a triac.

Use of a triac allows the implementation of phase control of triggering as shown in Figure 56.10.

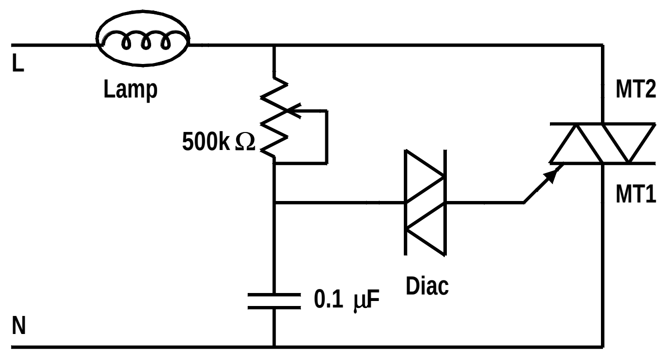

Figure 56.10: Phase angle triggering of a triac.

The variable $500\,\text{k}\Omega$ resistor and the $0.1\,\mu\text{F}$ capacitor allow a variable delay to be generated between the zero crossing of the mains voltage waveform and the time when a trigger pulse is applied to the triac. A device called a diac is used in this circuit. The diac does not conduct until the voltage across it reaches about 20 V. It then conducts and the resistance decreases rapidly so that, in the circuit in Figure 56.10, the diac dumps all of the charge stored in the capacitor into the gate of the triac and causes it to trigger. The effect of the CR and diac is to delay the application of the trigger pulse until some set time after zero crossing.

The resulting current flow in the lamp is shown in the diagram in Figure 56.11. As the value of the variable resistor is reduced, the voltage on the capacitor reaches the diac trigger voltage earlier and the triac is triggered earlier in the waveform giving nearly continuous variability in the intensity of the lamp. These circuits are available for use as dimmer switches. The circuit, as drawn in Figure 56.10, will generate substantial interference due to the sharp pulses at switch-on (high frequency Fourier components) which can

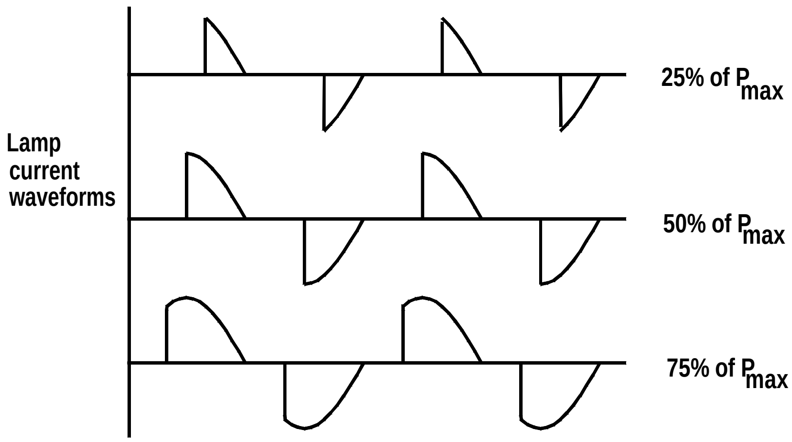

Figure 56.11: Waveforms in phase angle triggering circuit.

cause problems in radio reception and also cause problems of waveform distortion and harmonic loading for the power supply company. A commercial dimmer switch will have extra suppressor circuitry included which eliminates this interference problem.

When the electrical power supply to heaters, which have a longer time constant than lamps, is to be controlled, a better system is to use a zero volt switch system. These switches are available as made-up components containing all of the circuitry and the power control triacs in one package.

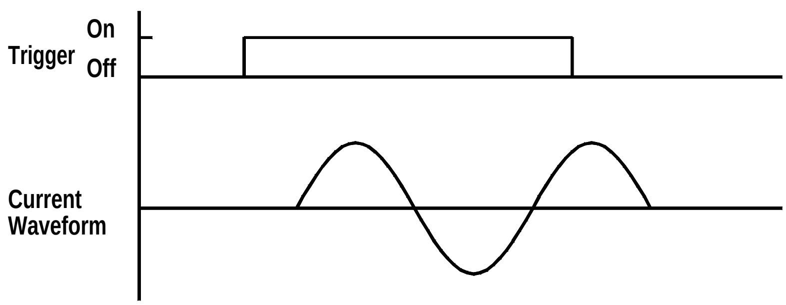

Figure 56.12: Waveforms in a zero volt switching controller.

In the operation of a zero volts switch, a DC signal current is applied at the control input which passes a current through an internal light emitting diode (led). The light is detected with a photodiode so that there is opto-coupled isolation between the input control signal and the power circuits. There are other internal circuits which are designed to block the application of trigger pulses to the gate of the triac until the zero crossing of the mains waveform. This causes the current to switch-on when the voltage is low and therefore the current surge at switch-on is minimized and the interference is also minimized. The result of this triggering strategy is that a whole number of half cycles of the mains flow through the load and the waveforms are as shown in Figure 56.12.

56.1 Problems

56.1 Calculate component values for a UJT metronome circuit in which the 100 Ω resistor in Figure 56.6 (c) is replaced by a loudspeaker and which uses a variable resistor in place of R to obtain a pulse repetition rate from 1 per 3 seconds to 10 per second.

56.2 Calculate the power dissipation in a load resistor as a percentage of maximum for triggering phase angles of 10°, 30°, 120°, 135° and 160°.

56.3 A 220 V_{RMS} waveform is applied to an RC filter of 120 kΩ and 0.1 μF. Calculate the time delay between the zero crossing of the driving voltage waveform and the time at which the voltage across the capacitor crosses 32 V. Will the time delay be different if the voltage across the capacitor is zero at the time of the zero crossing of the driving voltage waveform?

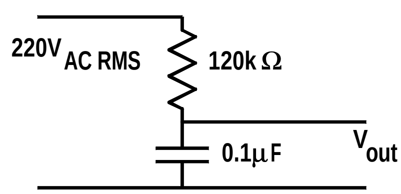

Figure 56.13: Problem 56.3.

56.4 A UJT oscillator, operating at a frequency of 100.2 Hz, is used to provide trigger pulses to the gate of a triac which controls the current in a tungsten filament bulb powered from a 50 Hz mains supply. Describe the variation of the light intensity from the bulb and justify your answer.