ELECTRICALLY OPERATED SWITCHES

By **KENNETH BRAMHAM**

Ranging from simple circuit breakers to electronic networks, they may use relays, vacuum tubes, thyratrons, or transistors. Characteristics of the various types.

ELECTRICALLY operated switches are the most important components in industrial and accounting electronics today. The familiar circuit breaker and the most elaborate "electronic brain" are both electrically operated switches. The circuit breaker must switch off a circuit when its current reaches a given maximum; the "electronic brain" must perform a multitude of switching operations to search for information, add, store new information, and finally switch on the correct electromagnet to operate a typewriter key or high-speed printer.

Vacuum tubes, soft tubes (thyratrons), relays, and transistors are all used as electrically operated switches. Each has its own characteristic advantages and disadvantages to make it more suitable for some applications than others. All have in common the ability to switch a much greater current than the input current controlling the switching. This of course is the equivalent of amplification.

An ideal switch responds instantly to its control voltage, has infinite resistance when "off," and no resistance when "on." In a practical switch these ideal conditions are never realized, but some of them may be approached closely at the expense of others. In every switch application, the relative importance of each ideal condition must be considered and the most suitable type of switch selected. Compromises must often be made, as in the many cases where low contact resistance is sacrificed to gain switching speed. Concessions may be necessary in order to use one type of switch throughout an installation for the sake of standardization. In some cases, concessions are made merely to allow the words "transistorized" or "electronic" to appear in the advertising.

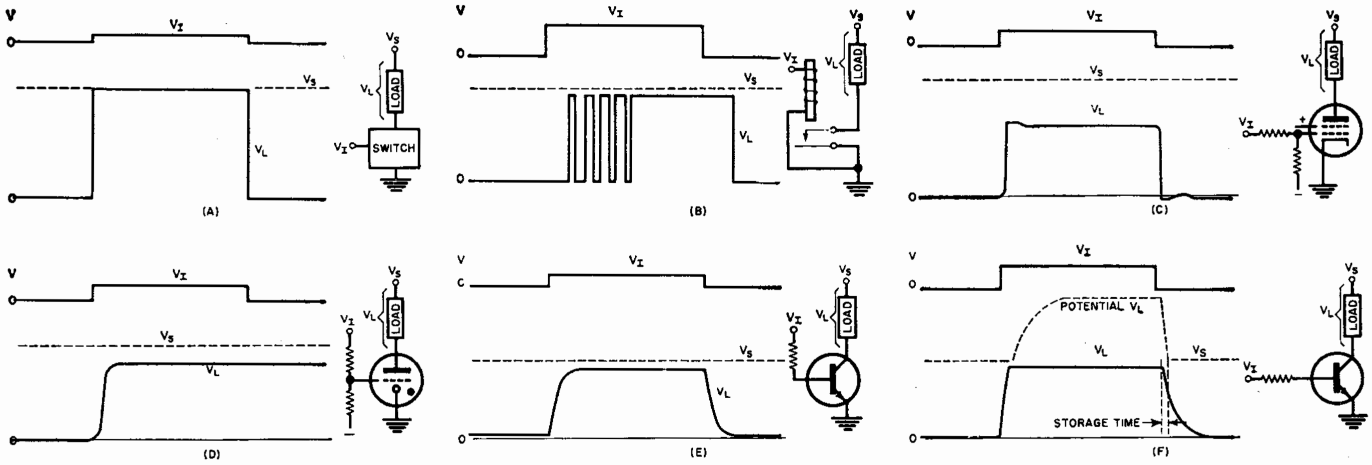
Plotting the control voltage or current, and the voltage or current being switched, enables us to compare the characteristics of different switches. Fig. 1A shows this graph using control or input voltage V_I and the voltage across the load V_L, for an ideal switch. Both input and output graphs are identical in time and shape, but not in amplitude. (Ideal amplitudes are not practical to portray, as the input voltage would be extremely small.)

Taking a "telephone type" relay as our first example and assuming the input voltage to be suitable for the relay coil, we see the resulting input-voltage and load-voltage graphs in Fig. 1B. There is a time lag due to electrical and mechanical factors after the input voltage is applied until the output contacts close. First, the inductance of the coil does not allow an immediate surge of current; the current in the coil, building up the magnetic field, is opposed by the back e.m.f. generated in the coil. The current in the coil and field build up exponentially until a steady state is reached, and then the current is determined by the resistance of the coil wire and the input voltage across it. Mechanical delay is introduced by the mass of the moving parts (armature and contact assembly) and the friction of the pivot bearings.

The total delay in this type of relay is from five to ten milliseconds to the first time the output contacts close. Now the energy due to momentum in the moving parts must be absorbed if the contacts are to remain closed; but, as all this energy is not absorbed, the contacts bounce open before being closed again by the field. This happens four times in our example, each time for a shorter open period, as the bounce distance decreases, until finally the output contacts come to rest.

Once the contacts are at rest, virtually the full supply current is available at the output. This is shown in the graph by the load voltage (V_L) being almost equal to the supply voltage (V_S). The contact resistance is negligible for most applica-

Fig. 1. Simplified input and output voltage waveforms for six common switches, showing differences in response of the output circuit to similar inputs. Waveforms have been drawn to heighten distortion and other output characteristics.



tions—providing the contact surfaces are in good condition. In use, a layer of oxide may form on the contacts and gradually increase the contact resistance, reducing the available output. Correct choice of contact material for the current and voltage to be handled, plus occasional cleaning, will overcome this problem in all but very low voltage circuits.

When the input voltage falls to zero, a time lag is again seen on the graph of Fig. 1B. First the energy in the magnetic field must be dissipated and then the mechanical factors must be overcome. The electrical portion of this delay can be varied over a wide range by introducing different circuits across the coil to slow the rate of energy dissipation in the coil. The mechanical factors are less predictable, being dependent on such matters as spring tension, lubrication, and temperature.

Other relay types have characteristics slightly different from the one shown. All have delay to a greater or lesser degree, and almost all but the mercury-wetted types exhibit a certain amount of contact bounce.

Vacuum tubes used as switches have an advantage over relays in speed and sensitivity. No mechanical parts are involved and inductance is negligible but, because of this, the circuit capacity (which can be neglected in the relay) now becomes the limiting factor in switching speed. Because grid (input) current is not needed in most applications, sensitivity is very high. For example, a voltage change of only 4 volts (−5v. to −1v.) and negligible current will switch a 6AU6 from cut-off to deliver 10 ma.

The voltage-time graph of a typical vacuum-tube switch is shown in Fig. 1C. Although the input is again a square wave, the output has become slightly distorted, and it does not cover the full range of available current. The inter-electrode capacity of the tube, plus the capacity introduced by wiring, combine with the plate and load resistances to introduce slight delay in the output. If this delay were constant over a wide frequency range, all the frequency components in the output would be delayed equally and delay—but not distortion—would be the result. As this is not the case (unless special peaking circuits are employed), the delay varies across the frequency range and the result is a distorted output.

The plate resistance reduces the available output well below the level of the supply voltage and causes heat to be dissipated in the tube. This heat dissipation leads to a size problem, as large tubes must be used to handle currents of more than a few milliamperes. Against this, we have the advantages of speed and safe, reliable operation at relatively high voltages.

Thyratrons (multi-element, gas-filled tubes) are slower-acting than vacuum tubes, but have the advantage of lower resistance once they are switched on. A typical graph for a thyratron switch is shown in Fig. 1D, where some delay and a slight rounding out of the V_L curve are noticeable when the tube is switched on. This delay and distortion is due primarily to two characteristics of the tube, the inter-electrode capacity and the time taken to ionize the gas. The ionization phenomenon starts in the region between cathode and grid when the grid is made positive and spreads rapidly through the tube in an "avalanche," comparable to the breakdown of a zener diode. The low-pressure gas that, in its normal state, is an insulator, becomes a conductor when ionized to close the switch circuit. Gas pressure and the type of gas used determine the ionization time, which may be a fraction of a microsecond or several microseconds.

The most obvious difference between the thyratron and other switches is the "switch-off" characteristic. Once the tube has fired, the grid has no further control over the tube: the only way to restore it to an "off" condition is to remove the anode voltage for sufficient time to allow de-ionization. This may be from 1 to 10 milliseconds, depending on gas type, pressure, and temperature.

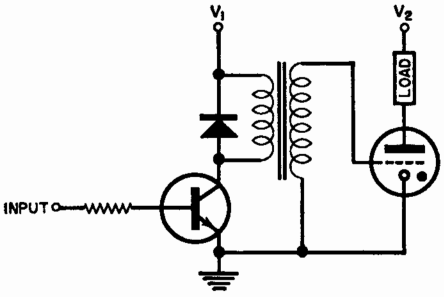


Fig. 2. A combination transistor and thyratron switch used to couple systems that have different supply voltages.

A switch that can be turned on but not off by its control element may seem to have very little use but, in fact, it is quite practical for many applications. Only a short pulse on the grid is needed to switch the thyratron on for an indefinite time; this can be used to advantage where a "hold" function is needed. To duplicate this effect and hold other types of switches "on," a flip-flop circuit must usually be used. This requires a minimum of two switch components. In another mode of operation, the thyratron plate is supplied from an a.c. or pulsating d.c. source that switches off the tube on each cycle and on again only when a voltage is present at the control grid.

Transistors, like vacuum tubes, are used both as signal amplifiers and as switches. The same transistor type may sometimes be used for either purpose but it is more likely that "steep-slope," special-purpose tubes or transistors would be used for switching applications. The requirements of a signal amplifier are that the output shall follow changes of input voltage or current very closely, while the switch requires only two states of output: "off" and "on."

Two basic switch conditions are used in transistor circuits, the low-level switch and the saturated switch. To simplify these conditions, the low-level switch can be regarded as being supplied with just the right amount of input drive current to give the required output current, while the saturated switch's input is *over*driven. If, for example, the *beta* (current amplification factor) of a transistor is 20 and the required output is 200 ma., the low-level switch circuit would be supplied with 10 ma. to the transistor base in a grounded-emitter circuit. The same transistor used as a saturated switch would be supplied with about 20 ma. to the base, twice the amount needed.

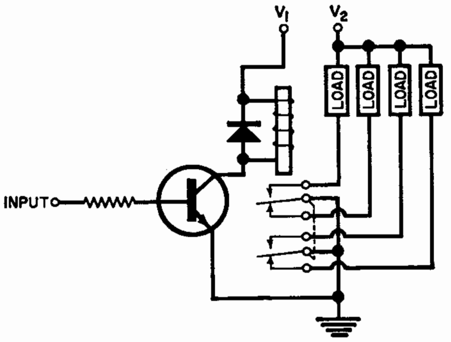


Fig. 3. Common office-machine combination. Transistor switch controls relay which, in turn, switches multiple loads.

At first glance, it may seem that we are wasting the potential gain of the transistor by saturating it. There are, however, advantages to offset the reduced gain. First we have the advantage of reliability and non-critical circuitry. The output current is limited only by the load. Variations in transistors or input circuitry must be quite large to have any great effect. Another advantage is faster switching to give a much shorter rise time, although a delay is introduced in the switch-off conditions due to "storage time" (the time needed by a semiconductor to become unsaturated).

The input and output voltage-time graphs for an unsaturated switch are shown in Fig. 1E and those for a saturated switch in Fig. 1F. The improved rise time and the delay due to storage time are seen in comparing these graphs. The broken-line graph in Fig. 1F shows the unsaturated state that would exist if the output voltage (V_L) across the load were not restricted by the supply voltage (V_s) and the same input current were supplied to the base. This unsaturated curve is useful in determining the saturated values of rise and fall time and

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the storage time. Note that it is also possible to *over*drive the switch "off," by applying a negative input voltage. In this way, storage and fall time are reduced.

Voltage limitations of transistors usually require that only transistors, or transistors and relays, be used throughout a system. It is sometimes necessary to couple two systems that use different switch components and work from different supply voltages. Special circuits are used to couple these systems without damaging the lower-voltage system. One such circuit is shown in Fig. 2, where a transistor switch is used to trigger a high-voltage thyratron. The transistor switch load is a step-up transformer, suppressed with a diode to prevent damage to the transistor from the kickback voltage; the output pulse from the secondary fires the thyratron. A very common combination, shown in Fig. 3, is the transistor switch used to control a relay. The relay, in turn, may be used to switch several circuits which would otherwise each require a heavy-current transistor or tube-switching circuit.

Temperature sensitivity is a disadvantage of transistor switches that must be overcome to achieve reliability. Heat generated in the transistor, due to the voltage drop across it while it is switched on, can cause the junction to fuse; while heat from the surrounding air can cause the switch to turn on even though the control pulse has not been applied to the base. A heat sink (a chunk of copper or aluminum) fastened to the transistor will conduct away the heat generated in the transistor. Careful circuit design must be used to prevent any sudden variations in the wattage dissipated by the transistor that the heat sink may not be able to handle, even though it is capable of handling the average dissipation. Correct biasing gives protection during the "off" time and prevents heat runaway.

The switches described are the ones most frequently used in automation and computer systems today. There are other switches, not described, that are being used to an increasing degree as new techniques are developed. Among these is the magnetic amplifier, used for years in heavy current and servo control systems and now finding new applications with the development of ferrites and multi-aperture cores. Esaki diodes and avalanche transistors are also taking over some of the work now done by older switch types. As each new switch is developed, it should take over where it is best suited, reducing the number of compromises made when a switch is selected, and increasing the reliability and efficiency of the systems of the future. ▲