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Electronic Digital Counters

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Recent advancements in all branches of science have created demands for high-speed counting devices. The development of the electronic digital counters, which are used for many purposes in the large computers, has made such fast computations possible. These counters, which use the binary system, are described in detail in this article.

THE PROCESS of counting or enumerating objects is, no doubt, as old as civilization itself, but the ability to count individual items at the rate of a million or more per second has been achieved only recently. Mechanical and electromechanical counters usually find an upper limit before the speed of 1,000 per minute is reached. The application of electronic circuits in this field has increased this limit well over 10,000-fold.

The basic process of counting, as we all know, consists of enumerating items one by one for the purpose of determining the total number in a given group. This process leads directly to other kinds of measurements. For example, the speed of a train can be determined by counting the number of rail joints or telegraph poles passed per unit of time. Time intervals also can be measured by use of the counting technique, as the swings of a pendulum can be counted from the beginning to the end of the interval.

A demand for higher counting speeds results from advancement made in the many branches of science. We are striving continually for higher speeds of moving bodies, greater distances into interstellar space, and finer resolution in submicroscopic studies. The art of making suitable measuring instruments must keep in step with such advancements.

MECHANICAL COUNTERS

Before considering the details of electronic counting circuits, certain mechanical counting devices and basic principles well may be considered. A well-known device of this character is the portion of an automobile speedometer which shows the number of miles traveled. Perhaps a better example of a mechanical device which illustrates the basic counting principle is the ratchet wheel and pawl. In this machine the idea of a multiplicity of stable states is well illustrated. The ratchet wheel has as many stable states as it has teeth, and the detent or "holding dog" will keep it at rest in any one of these states or positions indefinitely. The "counts" fed in by the pawl are accumulated one by one and the total at any time is indicated by the wheel position relative to its starting point. This typifies the ideal counter which receives counts uniformly or randomly at any rate up to its upper limit of speed.

In electronic counters the binary circuit is used extensively. This has two stable states and as the counts or pulses are applied, it trips alternately back and forth between these states. A good mechanical analogy of this is the chain-pull switch commonly used on electric lamps. As the chain is pulled, the lamp circuit alternates between its two states of being open or being closed. Two pulls of the chain complete one cycle of events.

A binary group of three switches could be arranged to have eight stable states. To set up such an arrangement, the circuit of the first switch and lamp would include a solenoid or magnet to pull the chain of the second switch and lamp. In a similar manner, the third switch would be controlled from the second. If the zero or starting condition occurs when all three lamps are on, two pulls on the first chain will turn out the second lamp, four pulls will turn out the third lamp, and seven pulls will leave all three lamps out. It is evident that the condition of the lamps will tell how many pulls or counts have been applied, and the entire cycle of events will be repeated for each group of eight applied impulses. Such a system has little practical value but it illustrates the binary-chain principle.

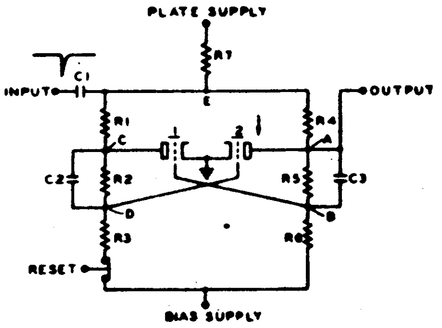

Figure 1. Locking-type multivibrator

ELECTRIC COUNTING ELEMENTS

In searching for electric circuits suitable for counting purposes, the use of capacitors for storing charges appears at first to be a promising possibility. Steps of equal charge can be fed into the capacitor and its potential difference then would be a measure of the number of counts it had received. Although this principle is successfully used as a frequency divider, it is not satisfactory for all counting purposes because of leakage difficulties. The major part of leakage of charge is due to the auxiliary circuit components which must be included for stepping and indicating.

A device is needed which has stable states that will hold

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indefinitely. A basic circuit of this character has been known for about 30 years. It is shown in Figure 1 with a few added features. In this circuit of two triodes, the cross coupling between plates and grids causes the system to be stable only when one section is conducting and the other is cut off. If the right-hand triode *2* is conducting or on, then its plate (point *A* in circuit) will be at a relatively low potential, while the plate of section *1* will be high due to nonconduction. Point *A* being low will allow point *B*, which is the grid connection to triode *1*, to be low enough in potential to produce cutoff in triode *1*. At the same time point *D* is held relatively high because *C* is high, and since *D* is connected to the grid of triode *2*, conduction will take place here. In a well-designed circuit this condition is very stable since triode *1* is biased well beyond cutoff and triode *2* is held conducting with its grid slightly positive. Since the circuit is symmetrical, the other mode or state, with triode *1* on and triode *2* off, is equally stable.

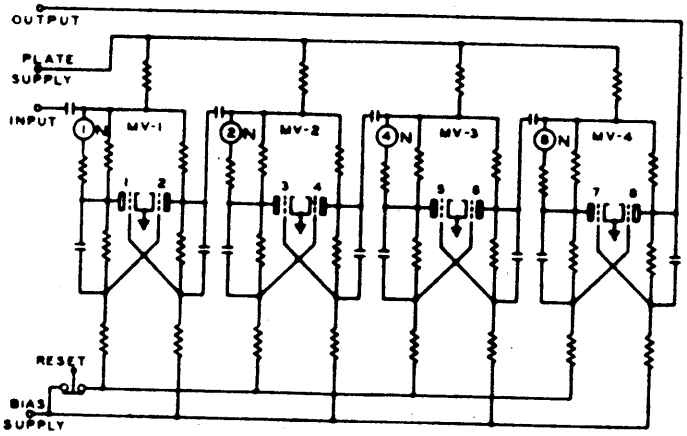


Figure 2. Binary chain of four multivibrators

Assuming again the initial condition of triode *1* off and triode *2* on, the action when an input driving pulse is applied will be investigated. In the circuit of Figure 1 a negative-polarity pulse is applied through capacitor C_1 to the common plate-circuit resistor R_7. Some of the pulse energy will travel through plate resistor R_4 and be dissipated largely in the low impedance of conducting triode *2*. Part of it may reach the grid of the triode *1* by way of C_3 but no action results from this since triode *1* is cut off. A second portion of the pulse energy will find its way to the grid of triode *2* by way of plate resistor R_1 and capacitor C_2. The resulting negative swing in this grid voltage causes a reduction in plate current in triode *2* and raises its plate potential slightly. This increase in plate potential drives the grid of triode *1* in the positive direction to start conduction through it. This initiates a drop in plate potential at *C*, which is transferred to *D* to reinforce the effect of the negative driving pulse. This loop feedback drive is highly cumulative and the circuit very quickly triggers over to its other stable state with triode *1* on and triode *2* off.

In a similar manner the next applied negative input pulse will return the circuit to the starting point. In practical use a reset switch may be connected, as shown, to open the bias lead. This causes triode *2* to go on (if it is not already on) and insures that the circuit is returned to its starting point. An output connection for a succeeding stage may be taken from point *A*. The input capacitor of this next stage will differentiate the output of triode *2* to give negative and positive drive pulses. Since a given stage responds only to negative pulses, there is a division by two in each binary stage.

This locking-type multivibrator possesses the essential requirements for counting purposes. First, it has a multiplicity of stable states (only two, however). Second, identical input pulses cause it to go from one stable state to the next. It also has the property of delivering output pulses which are identical or can be made identical with the input pulses. This points the way to a means of combining a group of binary stages to get any desired number of stable states.

BINARY GROUP

Figure 2 shows a group of four locking-type multivibrators connected in a binary chain. Such a series arrangement has a capacity of 16 counts. The value of the count at any time may be indicated by means of small neon lamps *N* arranged as shown. If these lamps are assigned the values 1, 2, 4, and 8 from left to right, the value of the count will be the sum of the values of the lamps that are on. Obviously, the length of a binary chain can be extended indefinitely to have as great a capacity as desired. The capacity equals 2^n, where n is the number of states.

BINARY DECADE

Since our numerical system is based on the decimal principle, the binary system is inconvenient to use. Figure 3 illustrates a binary chain of four stages with modifications that convert it to a decimal basis. This decade circuit, as it is called, has a capacity of 10 counts. The theoretical capacity of 16 is reduced to 10 by means of two feedback links. One feedback is from the left-hand triode of *MV-3* to the right-hand grid of *MV-2* and the other in a similar connection from *MV-4* to *MV-3*.

The operation of this decade can be better understood if reference is made to the chart of Figure 4 which shows the operating sequence of the four multivibrators. The top line shows the zero or starting condition with the right-hand triode of each multivibrator on. When the first input pulse is applied, *MV-1* is tripped over with its left-hand section on. The second input pulse returns *MV-1* back to the starting condition which sends a pulse ahead to trigger *MV-2*. After the third pulse is applied, the first two stages are both left with the left-hand sections on, while the last two stages have not yet been tripped. The operation this far has been according to the conventional binary-chain sequence.

The fourth input pulse produces a modified action. *MV-1* trips back to the right which causes *MV-2* to do likewise. This sends a pulse ahead to trip *MV-3*. As the left-hand section of *MV-3* goes on, a pulse is fed back to return *MV-2* to its previous condition which it held on the count of three. This feedback action is equivalent to advancing the settings of the entire chain by two counts and is the first step in reducing the capacity from 16 to 10. In other words, two counts have been lost or eliminated. The fifth input pulse trips *MV-1* again with no action elsewhere in the circuit. A second feedback action takes place when the sixth pulse is applied. *MV-1* trips back to the right which also trips *MV-2* to the right. This trips *MV-3* also back to the right but only momentarily because *MV-4* is tripped to feed back a return pulse. This action of *MV-3* is similar to that that took place at *MV-2* two counts previously. Advancing *MV-3* in this way results in reducing theoretical capacity by 4 more counts.

By means of these two feedback steps, the maximum possible capacity of 16 counts for four double triodes has been decreased by 6 counts to a new capacity of 10. The sequence of operation for the next 4 counts follows the conventional binary pattern, and after a total of 10 counts the decade is back to its starting point.

Although the arrangement of neon indicating lamps across plate resistors, as mentioned previously, could be used to show the recorded count, a better system would be to have a single lamp to light for each count. Figure 3 shows how this may be done by means of a network of 12 resistors. A combination of three voltages from the plates of three appropriate triodes is used to produce conduction in each of the ten indicators. One of these voltages is taken from a plate-resistor midpoint on *MV-1*. This determines whether an odd or even number should be shown. The other two voltages are taken in five combinations from the other three stages.

For the indication of zero, all the right-hand triodes are on. The upper terminal of the zero lamp is connected, by way of a resistor, to the left-hand plate resistor of *MV-1*. This places a relatively high potential on the upper side of the lamp. The lower terminal of the zero lamp is connected by way of two separate resistors to the right-hand triodes of *MV-2* and *MV-4*. These two points are both at relatively low potential so that the resulting potential across the zero lamp is great enough to fire it and keep it on. Each lamp in turn operates on a combination of one high-value voltage and two low-value voltages.

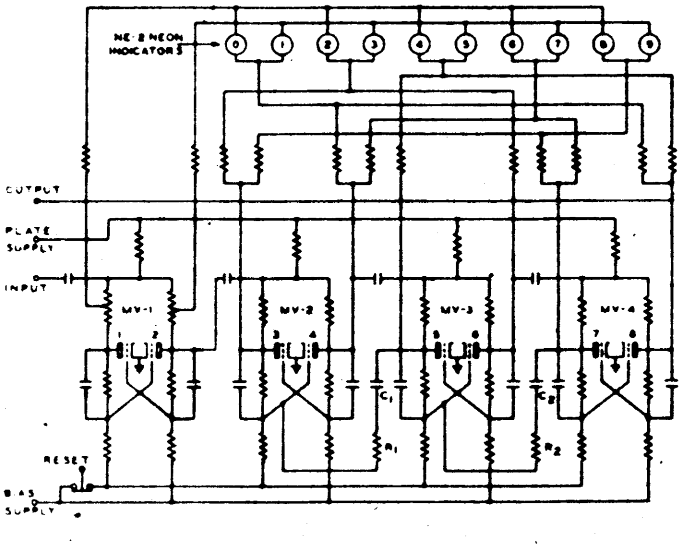
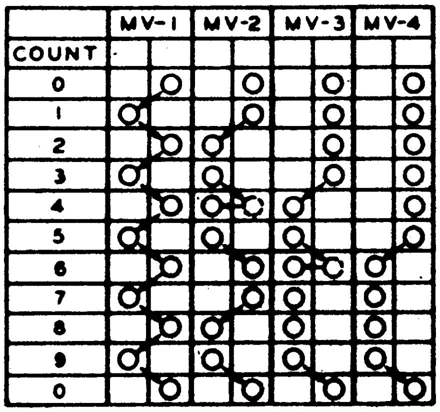


Figure 3. Binary decade circuit

OTHER COUNTER COMBINATIONS

Binary chains can be connected with suitable feedback links to have any integral capacity whatsoever. They also can be arranged in various compound relationships. Figure 5 shows a ring chain of multivibrators whose capacity in counts is equal to the number of multivibrators in the chain. In this combination one right-hand triode can be on while the others are off. The drive pulses are applied to all the multivibrators in parallel but only the "on" stage is receptive. As this "on" stage is tripped off, it triggers the next succeeding stage on. The count is indicated by whichever right-hand triode is on. This type of circuit is advantageous for certain applications but it is uneconomical in its use of tubes for general counting purposes.



	MV-1		MV-2		MV-3		MV-4	
COUNT								
0		○		○		○		○
1	○			○		○		○
2		○	○			○		○
3	○		○			○		○
4		○	○	◌	○			○
5	○		○		○			○
6		○		○	○	◌	○	
7	○			○	○		○	
8		○	○		○		○	
9	○		○		○		○	
0		○		○		○		○

Figure 4. Binary decade operating sequence

Figure 5 also shows two examples of a two-by-five system. This scheme often has been used to get a decimal count. Six multivibrators may be arranged in a series or a parallel arrangement. In these combinations the first stage counts by two's and a ring chain counts by five's. The indication of count is given by a combination of two voltages.

Another type of ring circuit is given in Figure 6. This uses gas tubes or thyratrons. The setup or preparation principle is used here. One tube at a time is conducting, and it prepares the next tube in the ring to receive the next drive pulse. This is done by causing the bias of any given tube to be supplied partially from the cathode resistor of the preceding tube. The prepared tube thus has less bias than other off tubes and so will be the next to trip. Kickback capacitors are connected between adjacent plates, so that when one of the gas tubes fires, it will extinguish the preceding one which had been on.

SWITCHING CIRCUITS

Practically all electronic counters require an associated switching circuit for initiating and terminating the flow of pulses to be counted. There are many circuits for performing this function; Figure 7 gives a circuit which has

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proved to be very satisfactory. It consists of a gate tube, a gate opener, and a gate closer. The gate or switch tube is a pentode, and its condition is controlled by the action of the other two tubes which are of the gas type. Gating is accomplished by raising and lowering the screen-grid voltage of the gate tube.

The incoming pulses to be counted, having positive polarity in this case, are applied to the control grid of the pentode. This control grid is biased well below cutoff so that plate conduction can take place only during each pulse peak, provided that the gate is open. During the initial or standby condition the screen is held at a negative potential so that there is no output irrespective of control grid behavior. This condition persists as long as the gate opener *A* and gate closer *B* remain untriggered.

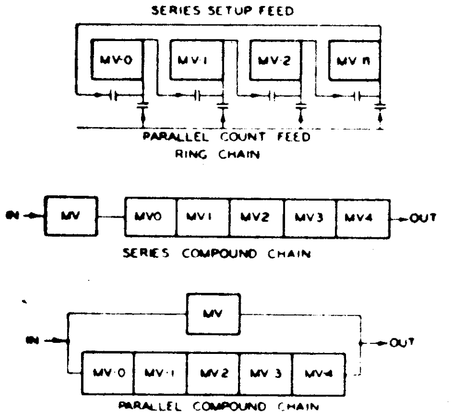

Figure 5. Binary chains

To start the flow of pulses through the gate, a start pulse is applied to trigger the gas tube *A*. As the gate opener fires, it suddenly raises the screen voltage of the gate pentode from the negative value up to the normal operating positive value. After this happens, each applied positive input pulse causes plate conduction which results in an amplified, negative-polarity output pulse. The gate remains open and the flow of output pulses continues.

To close the gate a stop pulse is applied to trigger the gate closer *B*. This gas tube quickly pulls the screen voltage of the gate tube back down to a negative value and the flow of output pulses ceases. Both gas tubes remain in the conducting state until the reset switch is pushed to restore the switching circuit back to its standby condition.

The wave forms of Figure 7 illustrate the performance just described. Although the input pulses are shown with a uniform occurrence rate, this obviously is not necessary. In some cases a sine-wave signal may be used on the control grid of the gate, and the output will consist of negative peaks of a clipped sine wave.

This gate or switching circuit possesses a number of features which make it most useful in many counter applications. The first of these is the lockout feature. This means that the gate will open and close only once without resetting, irrespective of further pulses applied to the gas tubes. A second feature is the interlock which prevents the gate closer from being accidentally tripped prematurely ahead of the gate opener. This sequence is assured since the lower gas tube has no plate voltage until the upper tube has been tripped.

The interlock may be further affected and given a controlled delay. This can be done by applying a portion of the gate voltage from the cathode of the opener tube to the grid of the closer tube through a delay network. With delayed interlock the start- and stop-pulse input terminals may be tied together for single-line operation. The first pulse to arrive on the line will open the gate and the next one will close it.

THE COMPLETE COUNTER

Although the essential parts of an electronic counter are the decades and switching circuit, other parts usually are included to make up a complete commercial unit. One model now available on the market has a 1-megacycle crystal-controlled oscillator, a switching circuit, six decades, and a power supply all included in a 9- by 11- by 17-inch portable case. This instrument has a capacity of one million counts and a maximum counting rate of one million per second. If it is used as a timer it will measure intervals up to one second with a resolution of one microsecond.

APPLICATION AS A STOP WATCH OR TIMER

Some of the functional details of counters having been described, applications will be considered next. Among these the application to time interval measurement has been important. Considering basic principles again, two methods of time measurement are to be noted. In one of these a continuously running timing element is used. A time interval is measured by noting the timer reading at the beginning and end of the period and taking the difference of the readings. This method is not too well suited to electronic counters because of the limited speed of response of the neon indicator lamps.

The better method of using the electronic circuit is the start-stop scheme, which is similar to using a stop watch. Electric pulses are developed to mark the beginning and end of the interval to be measured, and these are fed in to trigger the switching circuit. If the counter decades are initially set to zero and the cycles of an accurate oscillator are counted while the gate is open, the indicated result can be given as a decimal fraction of a second. If a stable 1-megacycle oscillator is used the measurement will be correct to ±1.0 microsecond.

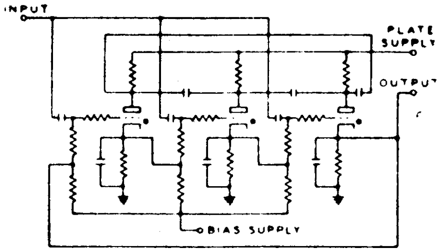

Figure 6. Ring-of-three circuit

There are many cases where measurements of this category can be made best with an electronic counter. For example, the performance of electromechanical devices

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can be studied. The closing or opening time of a relay can be measured easily.

One special case of electronic time measurement was in the field of nucleonics. The time interval to be measured was of the order of a few microseconds and this interval occurred only a few times per hour in a random pattern. To meet this problem a 6-stage binary chain was used and driven from a 4-megacycle oscillator. This gave a capacity of 16 microseconds with the accuracy of ±0.25 microsecond.

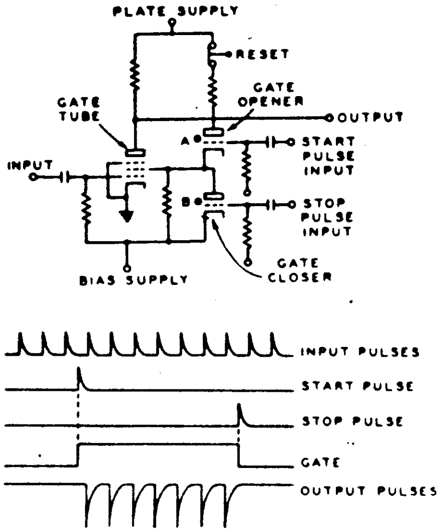


Figure 7. Gas tube switching circuit, and wave forms for switching circuit

Because of the long intervals between measurements, and since observations were made over periods of several days at a time, an automatic recording device was included with the counter. The record was made as a series of dots produced on teledeltos facsimile recording paper. After each operation, the paper was advanced and the electronic circuit returned to standby. A particular feature was that of automatic reset after 16 microseconds for cases where the start-pulse was not immediately followed by a stop-pulse.

FURTHER APPLICATIONS

Electronic counters have been used for several years in the measurement of projectile velocity. This is essentially a time interval measurement. The magnetized projectile is fired through two pickup coils, which are spaced a known distance apart. Passage through the first coil trips the gate opener and passage through the second coil trips the gate closer. The ratio of the distance to the measured time is the average speed.

Assuming that a counter having a 1-microsecond resolution is used, it is interesting to note that the accuracy of time measurement is comparable to the accuracy of linear measurement along the firing range. For example, if the projectile velocity is 3,000 feet per second it goes only 1 28 inch in a microsecond. A microsecond is very short indeed. Light travels only 980 feet in a microsecond.

Another application is in the measurement of frequency. In this case two counters are used. The first one is used as a timer to mark off a 1-second interval. The second counter counts the cycles of the unknown source for the 1-second interval, and its indication is the frequency expressed in cycles per second. The accuracy is ±1 cycle. Frequencies too high for a counter to handle may be reduced by heterodyne action.

In addition to these applications already mentioned, electronic counters find many uses in high-speed counting of objects. One of these is the pill counter. The circuit can be set to count off a predetermined number and repeat. This may be accomplished by presetting the decades to the compliment of the desired number and letting them run out, or a tripping pulse may be produced by coincidence of voltages selected from appropriate circuit points.

HIGH-SPEED OPERATION OF COUNTERS

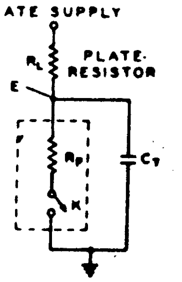
Because of the demand, considerable attention has been given to finding means of increasing counting speeds. In general, the same basic difficulties are encountered as those presented in wide-band video-frequency amplifier design.

As a first step in analyzing the problem, the circuit for one section or one-half of a binary stage may be reduced to the equivalent circuit of Figure 8. In this diagram C_T represents the equivalent total plate-to-ground capacity in the circuit. This includes not only the coupling and output drive capacity but also the stray and internal tube capacity. R_p is the dynamic internal plate-to-cathode resistance of the tube. Since electron transit time is not the first speed limitation encountered, the dynamic action of the tube may be represented approximately by the switch K. The condition for cutoff is with K open, and for conduction with K closed.

For high-speed performance, it is necessary that the swings in potential of point E, as the switch is operated, take place as rapidly as possible. For given values of R_L and R_p the speed of response is limited by the size of C_T. When the switch is opened, C_T charges through R_L, and when the switch is closed, it discharges through R_p. Obviously all three of these circuit elements should be as small as possible if the highest speed of operation is desired.

Although other considerations are involved, the value of R_L usually can be made as low as R_p. The ultimate speed of this circuit is then dependent on R_p and C_T, and is inversely proportional to their product. This condition may be expressed as

Figure 8. Equivalent circuit for high speed considerations



$$S = \frac{K}{R_p C_T} \qquad (1)$$

where S is the speed in some chosen unit, K is a units conversion factor, and R_p and C_T are as indicated in the diagram in Figure 8.

Although C_T includes external as well as internal capacitance, it still remains that the maximum obtainable speed depends primarily on characteristics of the tube. The foregoing expression may be modified somewhat to give a better factor of merit. Since the value of R_p depends mostly on how much current the tube will pass without injury, and this current is inversely proportional to R_p for a given voltage, the formula may be rewritten as

$$S = \frac{KI_T}{C_T} \qquad (2)$$

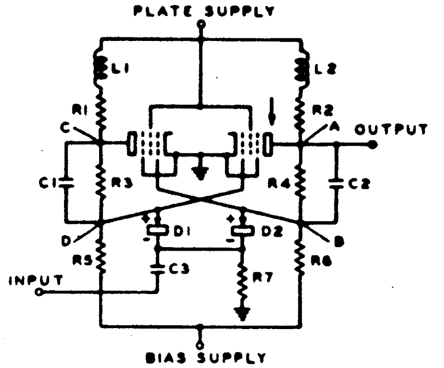


Figure 9. High-speed binary stage

If I_T (the tube current) is expressed in milliamperes, K is equal to unity, and C_T is expressed in micromicrofarads, then S is the factor of merit in milliamperes per micromicrofarad. In other words, this formula states that a tube suitable for high-speed operation should be able to handle as much current as possible with as low an output capacitance as possible, or more strictly speaking, the ratio of current to capacitance should be high. It is interesting to note that equation 2 obtained by simple deductions is also the equation for the maximum possible rate of voltage buildup for the conditions indicated.

Although this expression is the primary criterion to use in high-speed design, there are other factors to be considered. The tube also should have a high value of grid-to-plate mutual transconductance so that changes in plate voltage will produce sufficient changes in the opposite grid voltage to insure switchlike operation. Although R_L would be made comparable to R_p in value, too low a plate resistor would develop too low a plate voltage swing for good utilization. It should be remembered also that C_T includes all the plate-circuit output capacity and not that of the tube alone.

In addition to selecting the best tube, increased gains in speed can be realized by use of certain circuit features. Two of these are shown in Figure 9. The effect of the plate-circuit capacitance, as discussed, can be partly compensated by the use of plate-circuit inductances. The advantage gained by their use is similar to, but not as great as, that obtained in wide-band amplifiers.

The use of crystal diodes *D1* and *D2* in the drive circuit has led to greater stability and higher operating speeds than were previously attainable, since they offer several advantages. In the first place, their use allows the driving or trigger pulses to be applied directly to the grids through low-impedance paths. Because of the back-to-back arrangement of the diodes, this is accomplished without producing grid-to-grid coupling which would be degenerative.

A second advantage occurs on account of the manner in which the drive pulses automatically are distributed alternately to the two grids. This comes about as a result of the manner in which the diodes are biased through resistor R_7. If the right hand pentode is on, its grid terminal *D* will be at approximately ground potential. This will cause diode *D1* to have the same d-c potential of ground to exist on both sides of it. Diode *D2* will have its upper terminal at a much lower value of potential since it is connected to terminal *B* of the grid which is at cutoff potential. When a negative-polarity drive pulse arrives by way of input capacitor *C3*, it will be transmitted through *D1* but not through *D2* because of these potentials. As a result the initial part of the drive pulse will be applied only to the more positive grid and none of its energy will be wasted in driving the negative grid in the wrong direction. Because of these things, the binary stage of Figure 9 is very easy to drive even at speeds of several megacycles. As may be suspected, miniature pentodes have been found to be practical at such speeds. The use of such binary stages as these has made possible the development of a successful 10-megacycle decade.

CONCLUSION

All through this discussion on counters no reference has been made to the currently active field of electronic computers. Even though such a discourse belongs outside the scope of this article, a few closing comments may be of interest. The counter decade which has been explained in some detail can be regarded as one element that could be used for many purposes in a large computer. Its function in this role would be comparable to that of a number wheel in an adding or computing machine. Here again, the tremendous speed of the electronic circuit more than makes up for its complication. For a 10-position number wheel to match electronic speed, it would have to move at upwards of 100 million rpm. This illustrates the basic advantage of electron tubes in computing devices.

Although the 4-tube counter decade has been available only a few years, its rapidly increasing number of applications is proof of its importance. In most cases its function is that of a test or measuring device. In view of the increasing efforts being made in all branches of science, it appears that there should be a good future for electronic digital counters.

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MAGNETIC AMPLIFIER CIRCUITS
NEUTRAL TYPE

BY

ALAN S. FITZGERALD.

GENERAL.

All of the circuits described below refer to magnetic amplifiers of the neutral type. That is to say, their response is independent of the polarity of the DC input. For example, if the output of the amplifier is used to energize a relay, the latter will be operated in exactly the same manner by a given DC input current irrespective of the direction of flow of this current.

Magnetic amplifiers which respond selectively in accordance with the polarity of the input current will be dealt with in a further paper referring specifically to amplifiers of the polarized type.

The use of the direct-current excited saturating reactor as a control device dates back at least to the beginning of the present century,[1,2] and much activity has been manifested in the invention and development of responsive and control circuits featuring this device.[3]

The development, in 1925, of the copper oxide rectifier by Dr. Grondahl has very greatly increased the possibilities of saturating reactor circuit arrangements.

Considering the resourcefulness and diligence which have been applied to these efforts, it is remarkable how few of these ingenious schemes have found a permanent place in general engineering practice. With the exception of a few large theatre stage-lighting control systems, there is no application of saturating reactors in common use with regard to which information can readily be found in technical literature.

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[1] Lahmeyer, German patent No. 148,791, 1903.

[2] Burgess and Frankenfield, U. S. Patent No. 720,884, 1903.

[3] "Direct-current Control Reactor." *Electric Journal*, 28: 561-3 (1931).