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sidered in 1950 that such would be feasible at rural telephone stations which were also served by multigrounded neutral power systems and where power and telephone were commonly grounded. Active development effort on the problem, including the design of the protector, was begun 2 years ago and is still continuing. It is safe to say that the protector can be made at increased cost over the fuseless protector now used on stations served by metallic sheathed cables. In either case, there will still be a fusible element in the subscriber's circuit, namely, the terminal cable conductors and bridle wires.

The administration of fuseless protectors at stations on open-wire lines may yet prove to be a greater problem than the design of the device. This is due to the fact that careful attention must be paid to the ground to which the protector is connected. This is important for two reasons: The magnitude of the fault current that flows through the station protector is in part determined by the resistance of the station ground, and the potential difference between the power and telephone networks in the subscriber's home is proportional to the impedance between the two grounds. In the ideal case both utilities are grounded to an extensive public water-piping system with very low impedance to remote earth. A contact, therefore, causes considerable current to flow into the ground, blowing the station fuse or the fusible element in the drop wire run. The current, however, does not cause a dangerous rise in potential at the station with respect to remote earth, neither does it cause potential differences to exist between the power and telephone systems in the home. Unfortunately, many of the stations served by open wire do not have water systems. Bonding of the telephone ground electrode to the multigrounded neutral ground must then be resorted to in order to minimize potentials between the power and telephone wiring in the station.

A Magnetic Amplifier Switching Matrix

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By using conventional high-gain or bistate magnetic amplifiers as building blocks, switching networks may be derived which perform many computer or control functions. One such network which has been built and tested is a 4-digit binary-to-decimal translator. This translator was designed to provide a display in decimal numbers of binary-coded information. Basically a switching matrix made up of simple self-saturating magnetic amplifiers, this translator illustrates both the matrix technique and an advantageous application. The translator matrix operation, the specific bistate magnetic amplifier building blocks used, the decimal displays obtained, and their individual and combined characteristics are discussed in this paper.

Although magnetic core switching array applications in pulse circuits have been discussed in the literature,[1–4] the use of magnetic amplifiers to switch continuous power (rather than pulse power) has received little attention. In general, a bistate magnetic amplifier may be viewed as a contactless switch having some functional similarities to a relay. Without any moving parts, such a switch electrically isolates inputs and outputs, can provide high power amplification, and can be electrically set or biased to switch at a precise net signal value appearing in several control windings. In a manner similar to the application of magnetic cores in pulse-switching arrays, such bistate magnetic amplifiers may also be used in switching matrices. The matrix form and the building block magnetic amplifier used depend, naturally, upon the function performed, the inputs used, and the desired outputs. The specific matrix discussed in this report, a binary-to-decimal translator, acts, in effect, as a multiposition switch which distributes energy to any one of a number of positions in response to signal information. The translator accepts 4-digit binary-coded numbers on four leads and a common return, and it performs such translation and amplification that an easily read decimal number display is obtained from the 10-lead output with the use of either a 10-element neon gas tube or 10 filamentary lamps.

The translation problem arises from the need to present digital computer data in an illuminated decimal number display. With the binary computer involved, the number selected for display is converted to parallel binary-coded decimal so that each decimal digit of this number appears on four leads as a 4-digit binary-coded word. For each decimal digit there is then required a further translation from the binary-coded decimal to one out of 10 decimal signals with which to light indicating lamps or devices. This is accomplished by a magnetic amplifier-switching matrix or translator. The 4-digit binary-to-decimal conversion table in Fig. 1 shows the binary inputs and the required translation. As obtained from the computer logic packages, a binary "1" signal has an average value of 1.4 volts. The binary "0" is the absence of any signal or zero volts.

The operation of the magnetic-amplifier translator matrix to select one of 10 outputs in response to the binary inputs is described in the following section. Two types of magnetic-amplifier building blocks which have been used in such a matrix are discussed in the section "Bistate Magnetic Amplifier Switches." Discussion of decimal displays and translator characteristics, and the conclusions follow in that order.

Magnetic Amplifier Translator Matrix

For each decimal digit in the display, the associated binary to decimal translator has 10 possible 4-digit binary inputs as shown in the table of Fig. 1. With each binary input a unique one of 10 bistate magnetic amplifiers in a matrix is triggered ON while the others are held OFF. Only the fired (or ON) bistate unit transfers electrical power to its output lead so that for each binary input only one of 10 output leads is energized. The energized lead then causes a decimal number to be displayed. The schematic of such a matrix is shown in Fig. 2.

Fig. 2 shows 10 bistate magnetic amplifiers with their control windings arranged in a 4-by-10 matrix. The eliminated control windings, which would have filled the matrix, are not needed because the selection of the matrix is one of 10 inputs rather than one of 16 bits available from a 4-digit binary word. In this instance, half-wave magnetic amplifiers consisting of one core with a power winding, several control windings, and a bias winding are shown as the bistate units of the matrix. The dots indicate winding polarities, with current which enters the winding through a dotted end called positive. Thus, with the indicated bias current direction and bias winding polari-

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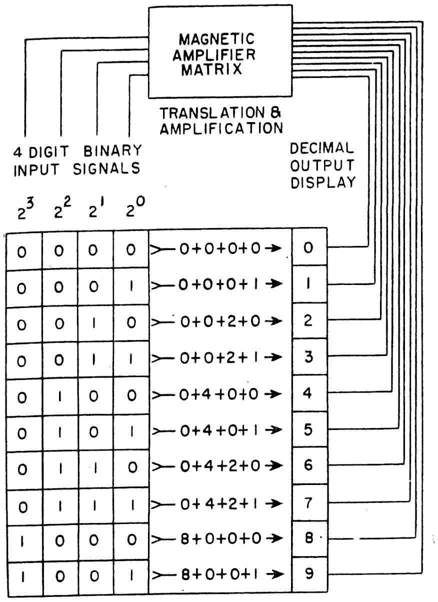


Fig. 1. Binary coded decimal-to-decimal translation

ties, all the biased units have negative ampere turns bias. The bias windings are weighted by having N_B, $2N_B$, or $3N_B$ turns as indicated in Fig. 2. All control windings have equal turns (N_C).

To explain the operation of the matrix, the bistate units may be assumed to have an idealized transfer characteristic as shown in Fig. 3. The output state (ON or OFF) is determined by the net control or the algebraic sum of the ampere-turns of all the control and bias windings on a bistate unit. Any binary digit 1 input causes an average control current I_c to flow through the control windings of the associated column in the direction indicated in Fig. 2. Therefore, on a per-unit basis with N_cI_c as a control unit, a binary 1 signal in a control winding is a ± 1 control where the sign is determined by the polarity of the control winding. With a binary 0 input there is no current flow. The bias current (I_B) is set so that $|N_BI_B| = |N_cI_c|$, or on a per-unit basis, the bistate units having N_B turns are biased to -1, those with $2N_B$ turns to -2, and those with $3N_B$ turns to -3. As seen in the transfer curve of Fig. 3, any unit with zero or greater net control is fully ON. Any unit with -1 or less net control is fully OFF. Now, observing the bias values and the control winding polarities, the table of Fig. 4 can be constructed showing the net control (bias plus control input) on every bistate unit for each of the 10 binary inputs. For example, with a (0, 0, 0, 0) binary input, all the bistate units will have some bias value (-1, -2, or -3) except for the decimal 0 unit which has no bias. Consequently, only the decimal 0 unit, having zero net control, is ON. For any other input the 0 unit is driven off because all of its control windings have negative polarities. For a (0, 0, 1, 1) binary input, only the decimal 3 unit will have zero control while all others are negative. For instance, unit 7 will have a bias of -3, a $+1$ control in the 2^0 column, and a $+1$ in the 2^1 column, yielding a net control of -1. The table, Fig. 4, which tabulates all these values, clearly shows that for each of the 10 binary inputs, a unique one of the 10 bistate devices is driven on.

The particular switching matrix described switches electric power suitable for directly operating the output displays. The two output states of the bistate units here employed are a continuous voltage or practically no voltage output as derived from the a-c power supply. In the pulse circuit magnetic core matrices, which are more widely discussed in the

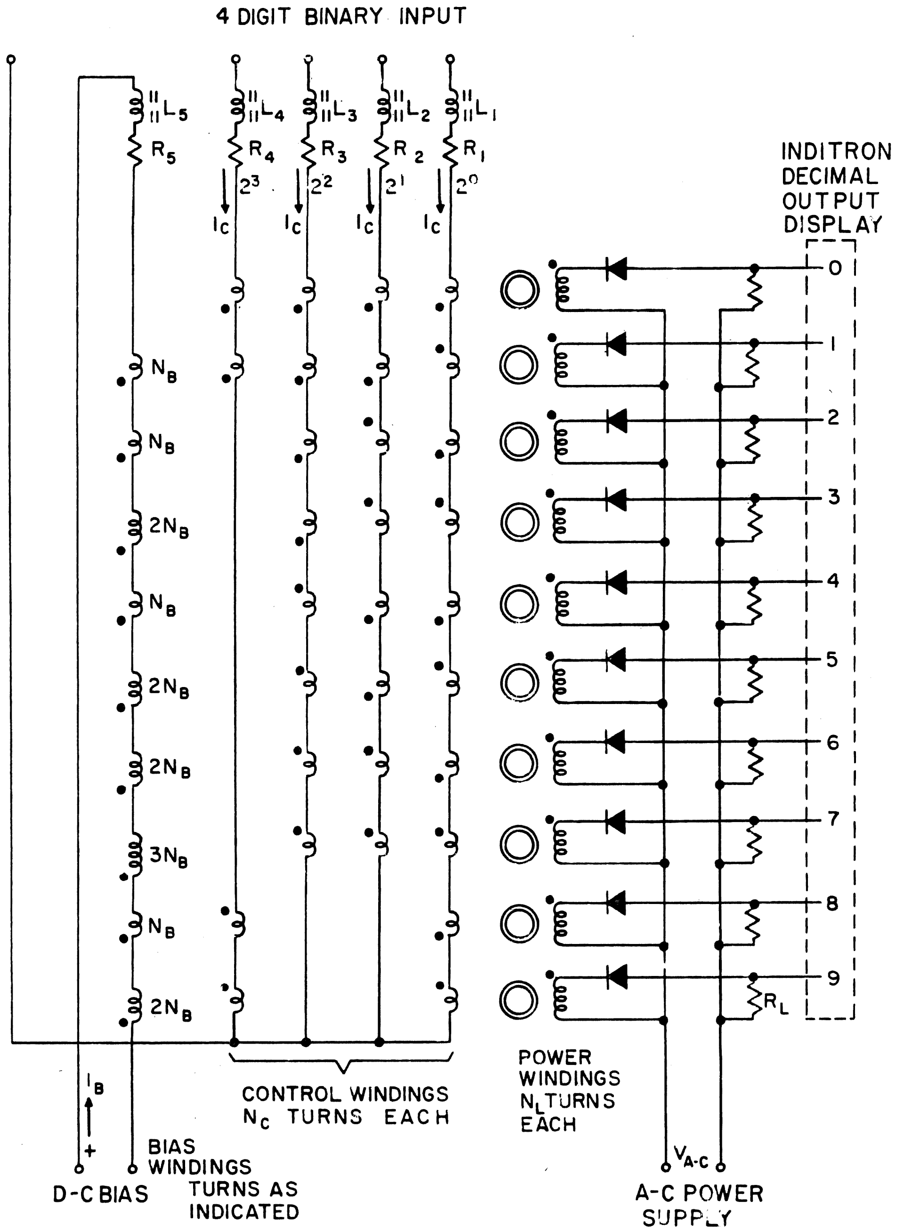


Fig. 2. Magnetic-amplifier translator matrix

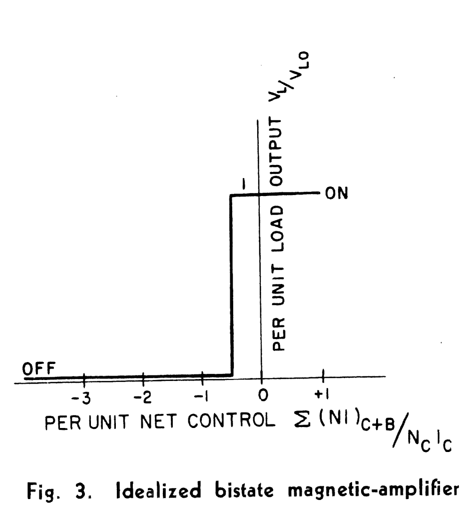


Fig. 3. Idealized bistate magnetic-amplifier transfer characteristic

Binary inputs (2^3 2^2 2^1 2^0)	Bistate unit number 0	1	2	3	4	5	6	7	8	9
	Per unit net control									
0 0 0 0	0	-1	-1	-2	-1	-2	-2	-3	-1	-2
0 0 0 1	-1	0	-2	-1	-2	-1	-3	-2	-2	-1
0 0 1 0	-1	-2	0	-1	-2	-3	-1	-2	-1	-2
0 0 1 1	-2	-1	-1	0	-3	-2	-2	-1	-2	-1
0 1 0 0	-1	-2	-2	-3	0	-1	-1	-2	-1	-2
0 1 0 1	-2	-1	-3	-2	-1	0	-2	-1	-2	-1
0 1 1 0	-2	-3	-1	-2	-1	-2	0	-1	-1	-2
0 1 1 1	-3	-2	-2	-1	-2	-1	-1	0	-2	-1
1 0 0 0	-1	-2	-1	-2	-1	-2	-2	-3	0	-1
1 0 0 1	-2	-1	-2	-1	-2	-1	-3	-2	-1	0

Fig. 4. Per-unit net control on individual bistate units for each binary input

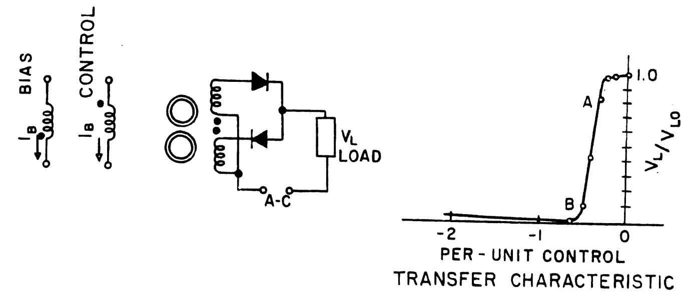


Fig. 6. Doubler circuit

literature[1–4] the output derived from a read-out current pulse is a voltage pulse or no pulse indicating one of two core flux states.

Assuming a bistate magnetic-amplifier transfer characteristic as in Fig. 3, which can be closely approximated in practice, one soon realizes that switching matrices utilizing such building blocks embody several desirable characteristics. Foremost, the switching is relatively insensitive to changes in the amplitude of the power supply voltage. Secondly, the output voltage of the nonselected units are negligible in comparison to the selected unit's output voltage. Switching ratios (the ratio of the output voltage at the ON state to the output voltage of the OFF state) of from 5 to 500 are common for magnetic amplifier bistate units. Further, there is considerable margin for the amplitude of the binary input signals. The matrix is also extremely economical of power and shows every indication of being economical in size and weight.

Bistate Magnetic Amplifier Switches

Recent papers and articles[5–7] both here and abroad about bistate magnetic amplifiers attest to the increased interest in such devices. In the translator matrix described, two types of magnetic amplifiers were used as the switching elements. These are the half-wave circuit, Fig. 5, and the doubler circuit, Fig. 6. The transfer characteristics, obtained from particular designs of the circuits which were used in laboratory matrices, are shown alongside each circuit. These curves are plotted on a per-unit basis (normalized) with the binary 1 input control current value (I_c) as the control unit and the zero control output load quantity (I_{L0} or V_{L0}) as the load unit.

From these transfer curves, it may be seen that the switching units of Figs. 5 and 6 are bistate by virtue of the digital-control input which is a 0 or $a \pm 1$ per-unit control. Actually, the points on the steep part of these characteristics are stable. If it were desirable, as in an analogue-to-digital conversion, the doubler circuit of Fig. 6 could be designed so that there would be truly no stable points between the two output states. This is commonly done by adding positive external feedback as is shown in Fig. 7. With increasing amounts of positive feedback the slope of the steep part of the transfer curve (AB in Fig. 6) increases through infinity and becomes negative, i.e., the curve theoretically bends back upon itself. However, since the points of infinite or negative slope are unstable, the transfer characteristic takes on the form shown in Fig. 7.

With a digital-control input, high-gain magnetic amplifiers, such as those of Figs. 5 and 6, make very satisfactory switching elements. Since a control signal is either a 1 or 0 on a per-unit basis and the bias is some integral multiple of the 1-per-unit control, these magnetic amplifiers can have only one of two outputs, either OFF or ON. However, for the translating matrix of Fig. 2, the closer the switching unit's characteristic is to the ideal characteristic of Fig. 3, the closer will the permissible variation of the binary input signals approach a theoretical maximum of ± 20.8 per cent (%).

The half-wave circuit of Fig. 5 uses only one core and one diode, but necessitates a high impedance to alternating current in every control and bias loop in order to minimize the transformer action between load and control meshes. In the steep region of the transfer curve, AB in Fig. 5, the gain or slope varies inversely with the induced a-c components in the control meshes. Consequently, in the translating matrix, Fig. 2, which uses half-wave magnetic amplifiers, there is required an inductor, L_1, L_2, L_3, L_4, and L_5, in each control mesh. Series resistors, R_1, R_2, R_3, R_4, and R_5, are padding resistors to compensate for winding resistance variations and to bring the loop resistance up to a desired value. The output of the half-wave circuit is, of course, half-wave recitfied alternating current. Since the Inditron gas tube display requires a direct voltage on the selected element, and since it was desirable to minimize the number of cores and diodes, the half-wave circuit was used in the translating matrix with a gas tube decimal display as shown in Fig. 2.

A balanced 2-core magnetic amplifier like the doubler circuit of Fig. 6 permits the use of low-impedance control meshes

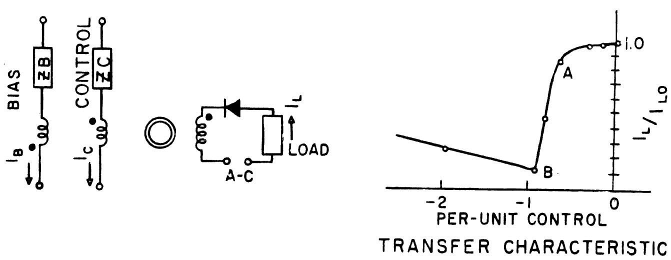


Fig. 5. Half-wave circuit

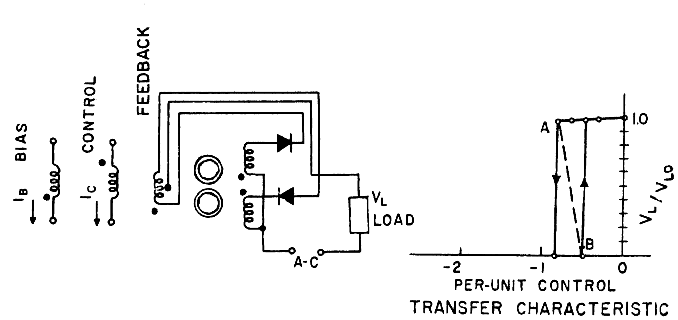


Fig. 7. Doubler circuit with external positive feedback

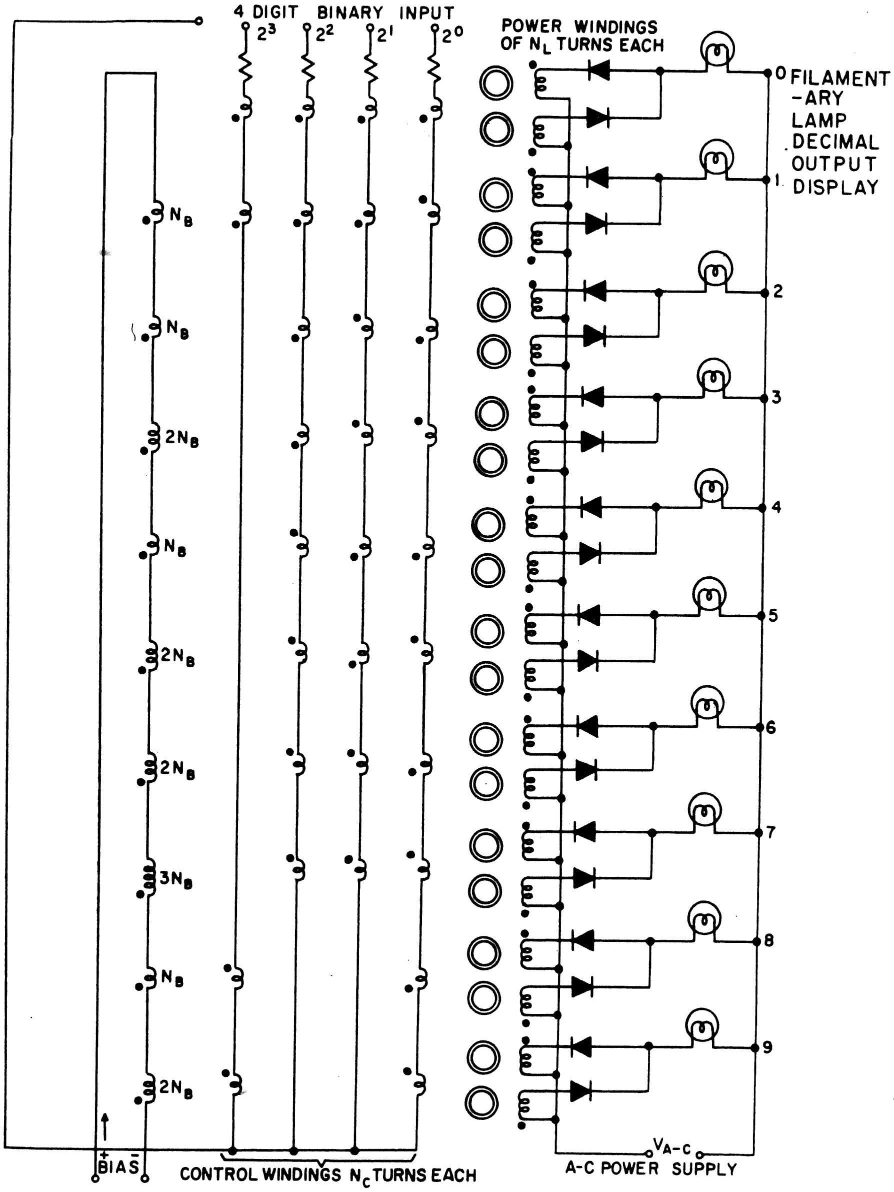


Fig. 8. Translator matrix

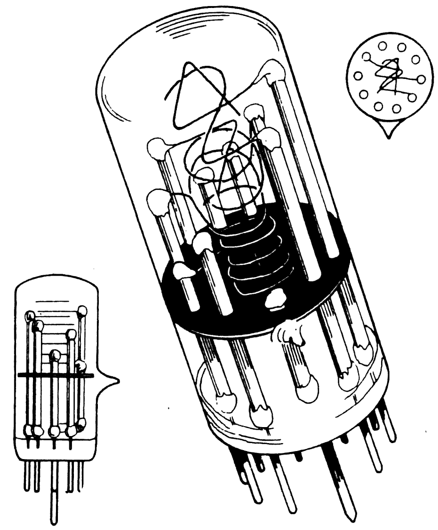


Fig. 9. National Union G1-10 Inditron neon decimal display tube

because the induced fundamental and odd harmonics of the a-c supply are bucked out in the control loops. Physically, this magnetic amplifier has two tape-wound cores each having an a-c power winding on it. These are then stacked and common control and bias windings are wound around the two stacked toroids. The output of the doubler circuit is alternating current. To provide a d-c output, two more diodes would be required for a bridge connection in the output circuit. However, for filamentary lamps the a-c output is satisfactory and the doubler circuit of Fig. 6 was used in a translator matrix with a lamp display as is shown in Fig. 8. The translator matrices of Figs. 2 and 8 are the same in principle and differ only in the type of magnetic-amplifier switch circuit used.

The doubler circuit eliminates the need for chokes in the control loops, does not severely restrict the number of control winding turns, and lends itself to the incorporation of positive external feedback. The last two factors permit very high-gain or true bistate magnetic amplifier operation.

The switching ratio of both the magnetic-amplifier circuits discussed here is a function of the number of power turns and the load impedance, for these largely determine the OFF-state output voltage. The switching ratio of the half-wave circuit, operating into a high-impedance load (51,000 ohms) in the translator, is close to six with the design values used. This ratio is more than adequate because the gas display tube's high breakdown and extinction potentials act to discriminate between ON and OFF switch output states. The doubler circuit, operating into a low-impedance filamentary lamp load (100 to 700 ohms), has a switching ratio in the order of 200. The filamentary lamp in the display requires a switching ratio of about 15.

The magnetic amplifier switches discussed are closely akin to magnetic-core switches used in pulse circuits. The former, however, use a continuous a-c power supply or drive to obtain a continuous ON or a zero OFF electrical output for the switch states, while the latter use a single-pulse drive to obtain a pulse or no-pulse indication of the switch states. Both types of switching elements have exceptionally long life, are reliable, and have large-power handling ability. The switching magnetic-amplifier's speed of response is, of course, limited to one or more cycles of the a-c power supply frequency. Although practically usable upper limits for the power supply frequency have not been investigated, there are indications that difficulties will be encountered at over 50 kc.

Decimal Displays

Two different devices were selected to obtain the illuminated decimal number display. One of these, a gas tube, such as the National Union Inditron, is preferred at present because of the clarity of the display obtained. This 10-element neon tube, with each element formed into

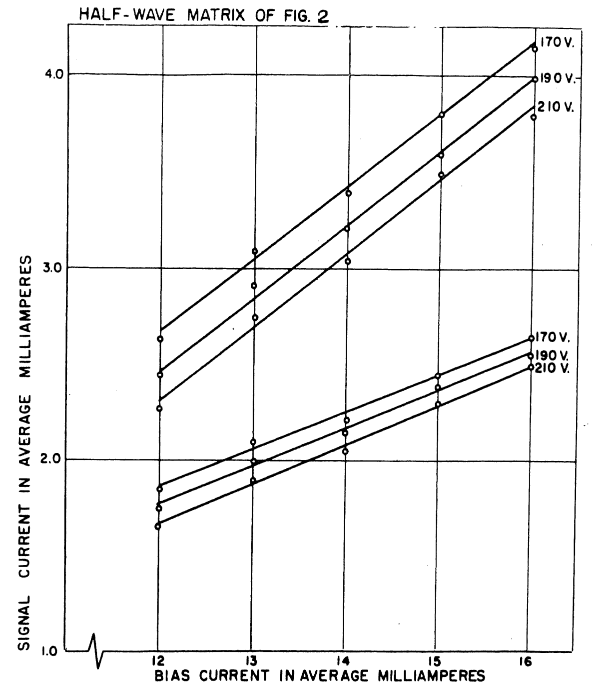


Fig. 10 (left). Maximum and minimum permissible signal currents versus bias current with the supply voltage as a parameter

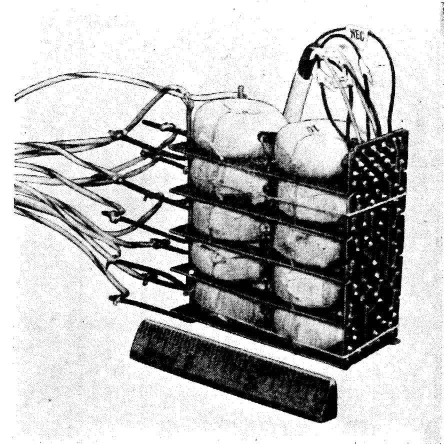


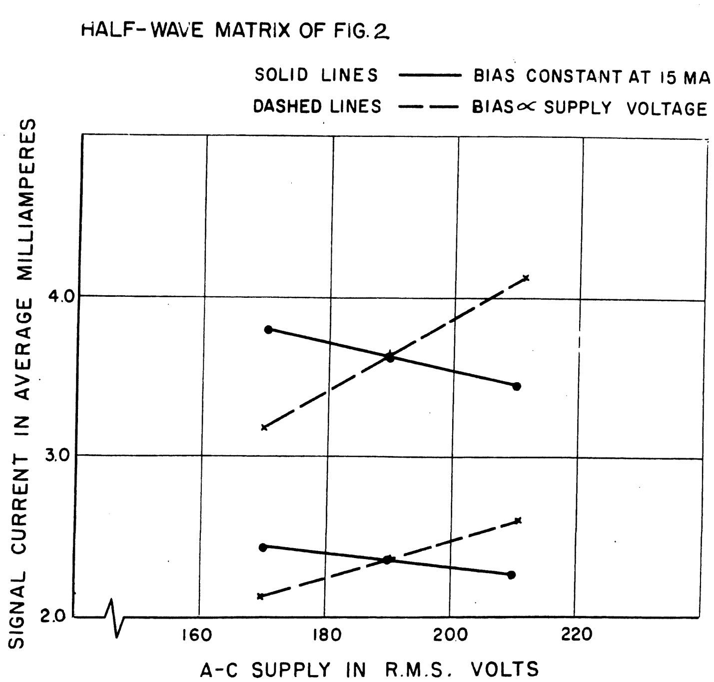
Fig. 12 (right). Laboratory model magnetic amplifier translator

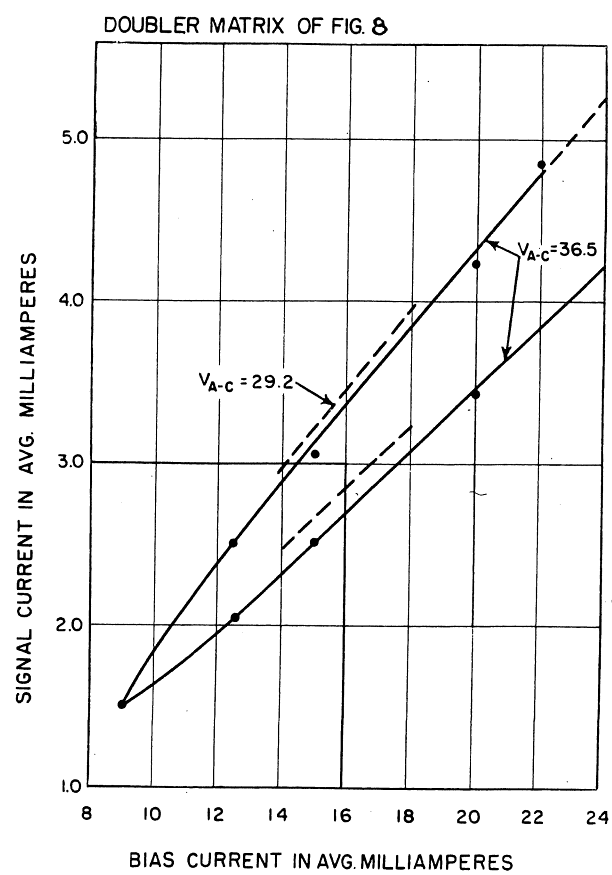
a decimal number from 0 through 9, is pictured in Fig. 9. With the half-wave rectified output of the half-wave translator matrix, the selected element is held about 125 volts rms more negative than the other elements. The selected element becomes a glowing cathode, the other elements act as shared anodes, and a well-defined, easily read decimal number display results. Since it requires a gaseous breakdown, the Inditron operates at relatively high voltages, approximately 250 peak volts. However, the high-breakdown and extinction voltages provide discrimination between ON and OFF switches and the power consumption of the gas tube is only 0.2 watt. The magnetic-amplifier matrix of Fig. 2 driving an Inditron provides a clear and reliable display.

The other display device consists of 10 filamentary lamps, each edge lighting a decimal number from 0 through 9 which is engraved in a lucite plate. A laboratory model of this type of display uses filamentary lamps rated at 28 volts and 0.04 ampere rms. The voltage required for this display is relatively low; however, the power consumption of about 1.25 watts is comparatively high. The driving translator for this display is the matrix of Fig. 8. Although this provides a readable and reliable display, the Inditron appears to give a better visual presentation.

Fig. 11 (below). Maximum and minimum signal currents versus a-c supply voltage

Fig. 13 (right). Maximum and minimum signal currents versus bias current





Translator Characteristics

The translator matrices of Figs. 2 and 8 using half-wave and doubler building blocks, have been built and tested. Since the Inditron display was preferred, a mock-up of a 5-digit decimal display with five half-wave translator matrices and five gas display tubes was assembled and demonstrated. For comparative purposes, one model of the doubler translator matrix has been built and operated. The specific designs of both types of matrices for which characteristics are given here operate with the same inputs. The binary 1 is 1.4 average volts and the binary 0 is zero volts. With a maximum current drain from the signal source of 4 milliamperes, these translators are designed for a nominal binary 1 signal current of 3 milliamperes average. The a-c power supply is 400 cycles per second.

Typical operating characteristics of a half-wave translator matrix with an Inditron tube are shown in the curves of Figs. 10 and 11. From the curves of maximum and minimum signal currents versus bias current (Fig. 10), it is seen that at 15-milliampere average bias and with a supply voltage of 190 volts rms, the binary 1 input signal current may vary between 2.38 and 3.62 average milliamperes. For a nominal binary 1 input signal current of 3 milliamperes, which is set by choosing the proper values of padding resistors R_1, R_2, R_3, and R_4, this means a $\pm 20.6\%$ tolerance for the inputs. With an a-c power supply voltage variation between 170 and 210 volts, this signal margin becomes $\pm 15\%$. A clearer picture of the translator's insensitivity to a-c voltage amplitude is given in the plot of permissible signal currents versus the alternating voltage, Fig. 11. The solid lines are for a constant 15-milliampere bias and the dashed lines are for bias proportional to the a-c supply voltage.

Other pertinent electrical characteristics of this translator may be listed as follows:

1. Frequency—A 5% variation in the frequency (380 to 420 cps) of the supply voltage has a negligible influence on operation.

2. Power consumption—The a-c power input required is less than 1/2 watt per translator.

3. Temperature—Temperature compensation over a range of -50 to $+60$ degrees centigrade can be made implicit in the design, for the temperature change in bias current can compensate for the change in signal currents.

4. Response Time—Switching from one decimal digit to another takes about 0.01 second with a 400-cycle power supply.

Physically, a laboratory model of the half-wave matrix appears as shown in Fig. 12, In production such units would utilize printed circuits and be cast in an epoxy resin. The chokes L_1, L_2, L_3, L_4, and L_5 of Fig. 2, are not included in the translator package. The packaged translator for a 400-cycle a-c power supply would measure about $1^7/_{16}$ by 3 by 3 inches and weigh approximately 1 pound.

At present, an equivalent translator using a 4,000-cycle a-c supply is being constructed. This promises to result in a space reduction of about 40% over the 400-cycle design. Although unsought in this instance, this increase in power supply frequency should also result in a reduction in switching time from 0.01 to 0.001 second. The higher frequency power source may be obtained from a magnetic-coupled multivibrator.[8,9]

The operating characteristics of the doubler matrix with a filamentary lamp display are shown by the curves of Fig. 13. At a 16-milliampere average bias, with a 36.5-volt rms 400-cycle supply, and again considering 3 milliamperes average as the nominal signal, the signal margin is slightly more than $\pm 10\%$. This could be increased by increasing the switching unit's gain so that its transfer characteristic approaches the ideal of Fig. 3. Greater gain could readily be realized with the doubler circuit by incorporating positive external feedback or increasing the signal winding turns. However, the difference between the signal margins of the half-wave and doubler matrices ($\pm 20.6\%$ versus $\pm 10\%$) is not due to any difference in transfer characteristics but to a-c induced effects in the control loops of the half-wave matrix which beneficially increase its margins. However, these induced effects, which are limited by the chokes, L_1, L_2, L_3, L_4 and L_5, must not be allowed to become too large, for there would be a concomitant loss in gain in each of the half-wave switching units. When this loss in gain is sufficient to move the point B on the transfer characteristic of Fig. 5 to the left of the -1 per-unit control, the translating matrix does not function properly.

The doubler matrix requires an a-c input power of 2 watts with the filamentary lamp using about 1.25 watts of this. Such a matrix would package in much the same manner and size as the half-wave matrix and would not require control loop chokes.

Conclusions

Basically, this report described a magnetic-amplifier switching matrix which switches power to one of 10 leads in response to a binary input on four leads and a common return. Such a matrix may employ any of several suitable magnetic-amplifier circuits as the bistate building block. Two circuits, the half-wave and doubler circuits, were used and demonstrated in laboratory matrices. The output of the translating matrix may be used to power devices such as indicating lamps or a gas display tube. These translators permit wide margins for input signals and power supply voltage, offer large power economy, are rugged and reliable, and require no more space than other equivalent devices. The decimal number displays derived are well defined and easily read.

This translator demonstrates one advantageous application of magnetic amplifiers as switching elements. Certainly, in switching circuits where switching times of less than 1 millisecond are not required and where continuous rather than pulse power is to be switched, bistate magnetic amplifier switches have much to offer and present such broad possibilities that their use for other applications in place of more conventional devices appears well worth consideration.

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