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James W. Davis, Warren L. Dexter, and Bob H. Smith

January 31, 1969

LAWRENCE RADIATION LABORATORY
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Berkeley, California

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ABSTRACT

A prototype automatic control system using crossbar relays for switching was built for experimental study. Eleven sets of these highly reliable and inexpensive relays can provide computer or manual access to the control of 1000 magnets or other regulated systems. The system consists of a computer, several manual-control panels, a set of crossbar relays, digital regulator references and actuating devices, and a corresponding readback system. The manual-control panels contain an address keyboard, which controls the crossbars, and a data-entry keyboard. The data are routed to the desired regulator reference or actuator. Since any number of manual-control panels may be used, each maintenance specialty can have its own control of the accelerator on "down" days. For automatic operation the computer simply replaces one of the manual-control panels. The coil-to-contact isolation in the regulator reference chassis and digital readout systems provide essentially infinite noise isolation between the accelerator and the control system. Without the computer the cost is comparable to a conventional manual-control system.

Design considerations of the special devices which are unique to this type of control are included.

Introduction

Control of a particle accelerator is essentially a problem in communication between the operator and the accelerator. The objective is to provide the necessary information transmission at minimum cost--the classical problem of communications engineering.

Few of the vast number of necessary communications channels require very high information capacity; most do not. For these latter, which account for most of the cost of a control system, crossbar relays appear to be well-suited. Examples of this kind of information are:

1. on-off control of equipment

2. control words for regulator references of magnet power supplies and high-voltage inflector and deflector power supplies

3. control words for rf and amplitude programmers

4. position information for servo systems for beam probes, television cameras, etc.

5. readback data from digital voltmeters, frequency meters, counters, and position indicators.

Crossbar relays lend themselves to computer operation easily. Small computers have become widely used in the experimental programs of many of the accelerators. In this application, they have become almost essential. In Berkeley there are seven small computers in operation at the Bevatron, one at the 88-in. cyclotron and two at the Hilac. Most accelerator designers feel that an electronic computer is a very useful instrument in an accelerator control system.

Lewis has described the first application of a computer to an accelerator control system[1]--that of the zero-gradient synchrotron (ZGS) at Argonne National Laboratory. The computer programs the magnet current, controls the start of the master oscillator, and actuates different devices within the accelerator and beam-transport systems during beam acceleration. The initial work borrowed heavily from the computer-control art in the chemical industry, but now has its own accelerator orientation. This work has progressed to the present, continually adding new computer functions.

While this work was proceeding at Argonne, a 10-GeV electron synchrotron was under construction at Cornell. Littauer decided to orient the control system design to the needs of a computer.[2] Recognizing the similarity between accelerator control and information transmission, he borrowed heavily from communications technology. He developed a very advanced control system using an electronically operated time-division multiplex communications system. The computer has not yet been added, but Littauer clearly intends to do so.

Another early example of an automatic control system has been described by David Struthers.[3] He developed an electro-mechanical time-division multiplex system which sets the 17 trim coils of the Berkeley 88-in. cyclotron from IBM cards. This system periodically compares the currents in the trim coils with the values indicated by the contact closures through the IBM card and readjusts the currents as necessary, to hold them at the reference values.

In another interesting computer-control study, Lancaster described the use of a computer to control the beam through the beam-transport system from the Bevatron injector to the Bevatron inflector. [4] It consisted essentially of six beam servo systems, with the computer performing the feedback functions. This work was intended only as a study in computer control, and the equipment has been disassembled. At present the computer is being reinstalled to control the beam-transport systems in the Bevatron's experimental area.

At Los Alamos, an extensive effort in the design of a computer control system was reported by Butler for the meson factory. [5] An interesting feature of this work is the application of computer display technology to reduce the vast amount of data associated with a large accelerator to a form in which it can be assimilated by an operator. Much of the data is presented on a computer display scope in the form of maps, graphs, and tabulations.

At this stage in the development of computer-control systems, one is impressed by the diversity of design philosophies of the different design groups. Lewis started his design from the point of view of chemical plant technology, Littauer from communications technology, Butler and Machen from scientific computer technology, Struthers from regulator technology, and Lancaster from servo system technology. Most of the groups have had as an ultimate objective on-line beam optimization. So far this has not occurred. Progress has been limited by the difficulties in making good non-destructive beam measurements. We need better beam detectors with high information capacity for beam current, beam emittance, beam position, energy spread, and microscopic and macroscopic duty factor.

However, it may be that on-line beam optimization is not a worthwhile objective. The accelerators are really very stable instruments. Most will maintain an optimized beam without attention for many hours and even when the beam does drift from optimum, resetting the offending electrical parameter restores it. A small computer with a large memory may be the most economical solution to the computer control question, and the only on-line requirement. If rarely required, beam optimization may be more economically achieved by a larger off-line computer operating from data taken by the small computer. Presumably the larger computer would be a general-purpose computation facility for all scientists associated with the accelerator and its experimental program.

An operator, by means of a computer and its memory, can organize the information to be transmitted into the most efficient form. It can be put on the accelerator communications system and transmitted to the many receiving stations. Crossbar relays appear to be well-suited to the switching functions of the control system. Eleven sets of crossbar relays provide 1000 channels. It can readily be expanded tenfold--enough for the largest accelerator.

We have been developing an automatic control system for the Omnitron. It includes a set of primary crossbar relays and as many sets as necessary of secondary crossbar relays. The primary crossbar relay connects the control panels to any one of the secondary crossbar relays. Each secondary crossbar relay is located at an information gathering station of the accelerator. For example, there would be a set of crossbar relays at each rf station, at

the switchgear room where magnet power supplies are located, at the injector area, and at each of the experimental areas. Each secondary crossbar set, consisting of five relays in parallel, provides access to 100 channels, each consisting of 20 twisted pair and five coax lines.

Design simplicity became important when preliminary specifications called for any one of 30 manual data-entry stations to be able to address any one of 10 000 remote actuating devices and to be able to transmit 16 bits (four decades of binary coded decimal) while maintaining extremely good electrical isolation between such sensitive devices as precision bending-magnet regulators and the noise sources of a vast control system. The isolation specifications (120 db), coupled with the necessarily low on-resistance of the switch closure in the precision regulator references, effectively eliminated everything but relays as the coupling medium at these interfaces. The relay decision having been made, parallel transmission became necessary in order to be able to set all the references in a reasonable time, given the relatively slow switching-time characteristics of relays.

Since the system speed had been effectively set in the centisecond region by the use of relays in the precision references and in the numerically controlled power contactors, we began to explore all basic functions in the system, with an eye to where we could use relays to advantage instead of where we could avoid their use. We found that, even in this day of transistor technology, relays offer many advantages in slow-speed systems. In the area of noise immunity, for instance, relays can offer orders of magnitude, and more, noise immunity than switching semiconductors. They do, of course, tend to generate some noise of their own and this must be taken into consideration in designing a system using both relays and semiconductors, either switching or not. Interestingly enough, one does not pay such a terrible penalty in using relays when the number of switching contacts is rather large, since the amount of coil necessary to switch ten relay contacts in parallel is not that much greater than the amount necessary to swing one single-pole contact. The switching points are actually smaller than a TO-18 transistor. In the present case, for example, the crossbar used is a 10×12 matrix switch with ten individual paths at each crosspoint. Thus, we have 1200 switched contacts complete with the necessary address-selection mechanism in a package roughly 9 by 23 by 6 in. More relay applications were found, until the system has eventually become completely relay-operated with the exception of the semiconductor blocking diodes used in selection "or" gates. An application for a one-shot in the manual data-entry panel was filled by a time-delay relay.

Figure 1 is an overall block diagram of the system showing the four information-transfer stages: manual-data-entry panel, primary crossbar, secondary crossbar, and remote data acceptor. Later figures will show that modularity is specifically designed into the system. In some cases voltage is applied to a selected line, and in other cases ground is applied to a selected line in such a way that an additional manual panel, for example, can be introduced to the system quite easily by simply tapping into the address-display busses in parallel with the manual panels that are already on those busses. In practice around the Omnitron, it is expected that the manual panels will be scattered physically all over the accelerator installation. At least one manual panel will be situated in the master control room, other manual panels are expected to be in the switchgear area, the rf stations,
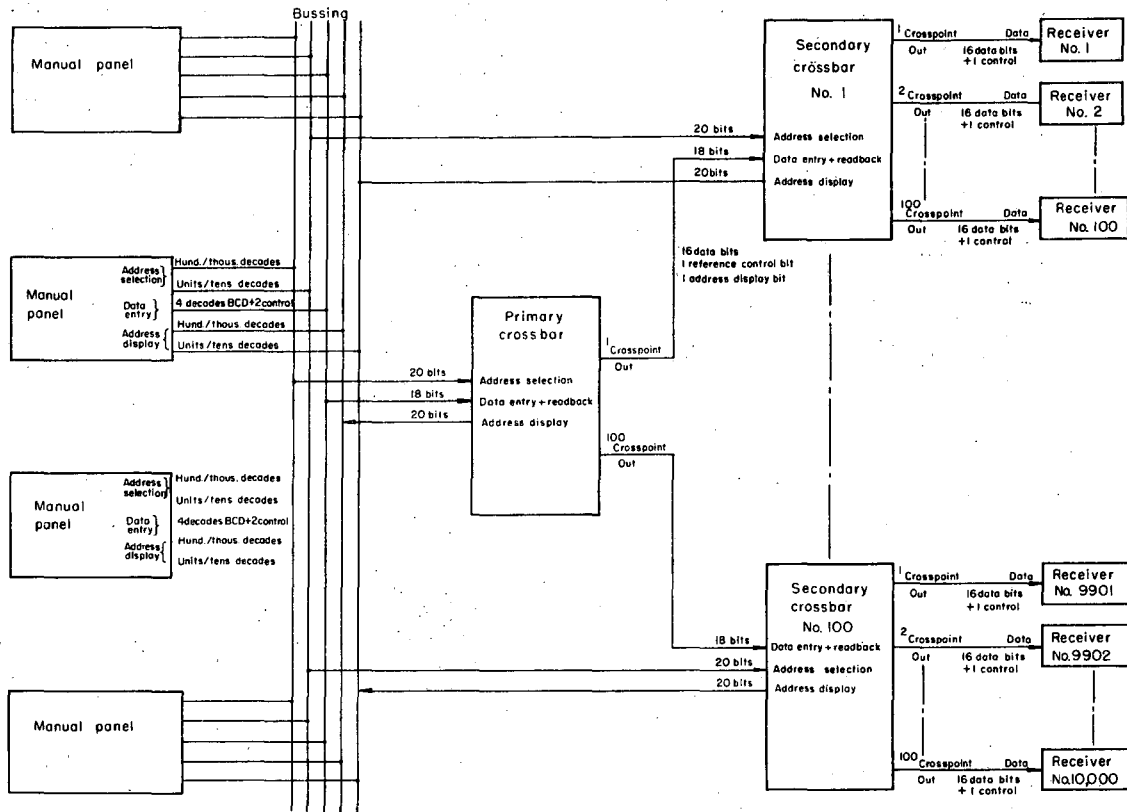
XBL692-1915

Fig. 1. Block diagram of control system. An electronic computer
    may be substituted for one of the manual data-entry panels
    for automatic operation. In addition to being installed in
    the main control room, manual panels may be located at
    any of the information-gathering centers of the accelerator,
    for example, at an rf station, switchgear room, or ex-
    perimental area.

the injector area and any area where people could reasonably be expected to need to call a remote station and set or reset it to a particular value. An application here could be in the beam switch yard. One secondary crossbar, for instance, could handle 100 beam-switching magnets.
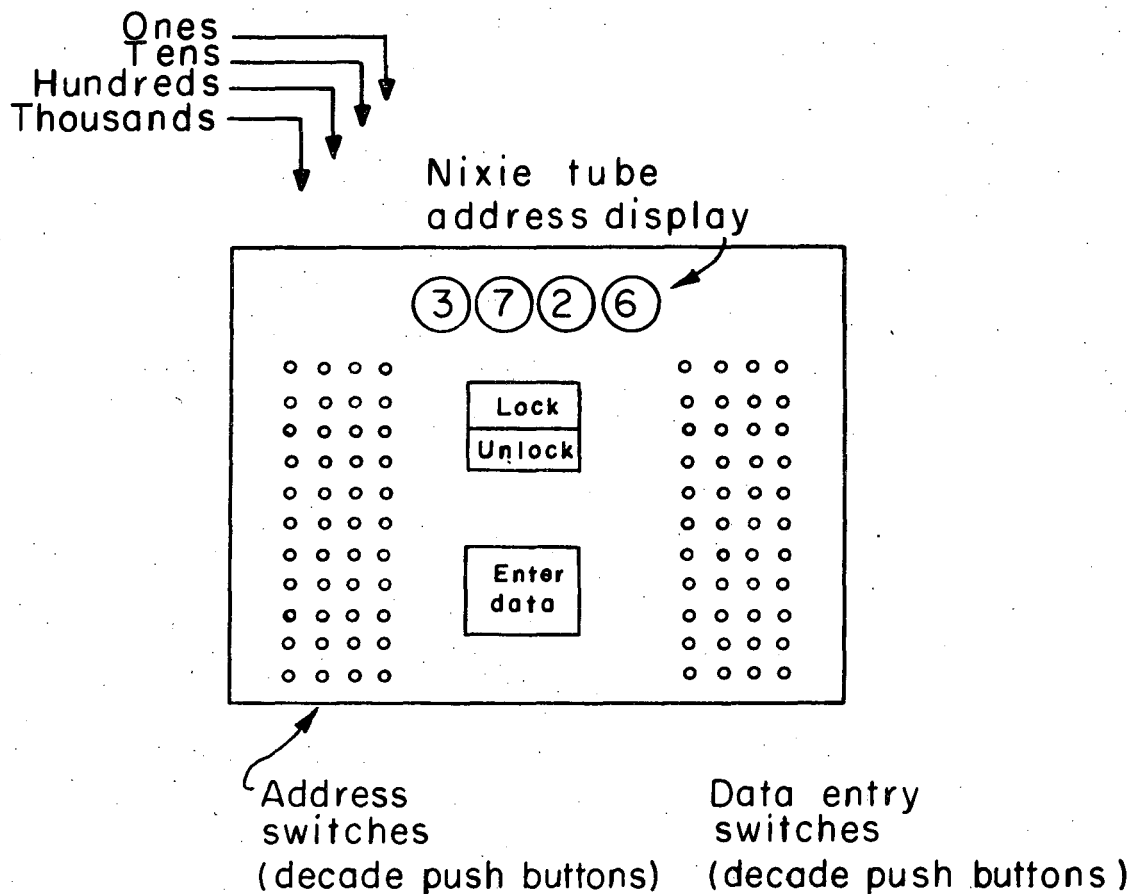
A later section will show that even though the manual data-entry panels are modular in design and construction and can easily be functionally paralleled by simple bussing, it is still easily possible to impose address lockout in the construction of the manual panel so that a given manual panel may not address certain remote terminals (much like a nine-level telephone block prohibiting some telephones within a company from calling out).

Figure 1 illustrates the three information transmission subsystems connecting the manual panel, primary crossbar, and secondary crossbar systems: address selection, data entry, and address display. The rest of this paper will be in six sections: one each devoted to the manual panels, the primary crossbar, the secondary crossbars, the regulator references, the numerically operated contactors, the high-current magnet-transfer switches, and computer integration. The term receiver is used throughout this paper to refer to any of the digitally operated output devices.

Manual Data Entry Panel

Figure 2 shows a physical layout of the manual panel illustrating the four decades of address-selection switches and the four decades of data-entry switches (data may be entered into the receiving device to a precision of 1 part in 10 000). The figure shows the two lighted push-button switches, the upper one being the "lock-unlock" access button, the other the "data entry" button. The figure shows also the four decades of address display. An address display is not strictly functionally necessary; however, the consequences of reading the right data into the wrong reference power supply can be disastrous. Thus we decided to provide a positive address display completely independent of the push buttons on each manual panel. The address-display section throughout the system is separated from the address-selection mechanism to the extent that the address display is conditioned not by which pushbuttons on the manual panel are pushed or even which magnets in the crossbar have voltage applied, but which actual switching points are closed.

Consideration of the address-selection mechanism in the manual panel area should start with observation of Fig. 3, with particular attention to the locking line. The locking line comes into the manual panel in three places, L1, L2, and L3. As Figs. 3 and 4 show, the locking line starting from a fixed power supply is run in series through contacts RE1-3 of each manual panel. After running through all the manual panels in series connection L2 to L3, it branches out to all manual panels in parallel at contacts L1. In this manner when any manual panel is locked on to the line, its RE1-3 contacts open, the series string is broken, and power is removed from the L1 terminal of all other manual panels, disabling them from being locked on the line. Power is, of course, also removed from the L1 terminal of the manual panel in question, causing power to be removed from the lock-unlock switch whose contacts, S1-1, pulled RE1 up in the first place. Consequently contacts RE1-1, diode D1, and voltage V are included to latch relay RE1 of the manual panel being placed on the line.

Ones
Tens
Hundreds
Thousands

Nixie tube
address display

③⑦②⑥

o o o o   o o o o
o o o o   o o o o   Lock
o o o o   o o o o   Unlock
o o o o   o o o o
o o o o   o o o o
o o o o   o o o o
o o o o   o o o o   Enter
o o o o   o o o o   data
o o o o   o o o o
o o o o   o o o o
o o o o   o o o o

Address   Data entry
switches   switches
(decade push buttons)   (decade push buttons)

XBL692- 1916

Fig. 2. Physical layout of a manual panel. Separate keyboards
     are used for address selection and data entry in order to
     reduce the probability of human error.
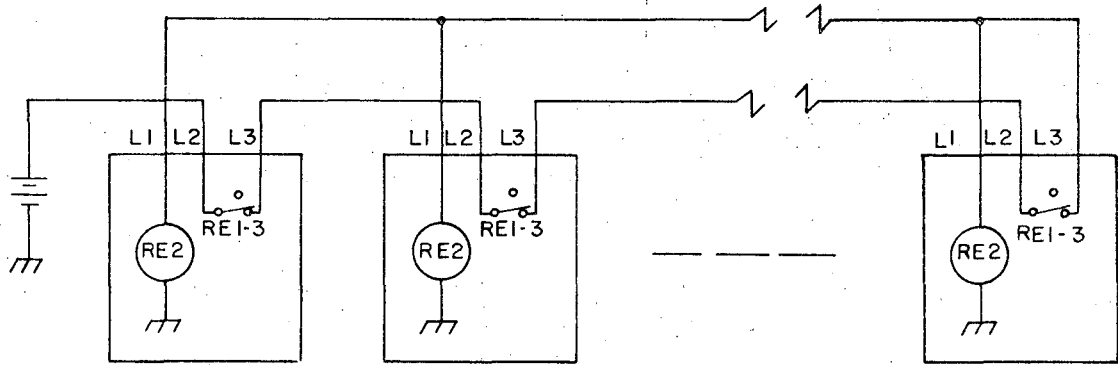
XBL692-1917

Fig. 3. Manual panel locking lines. When any manual panel is
        locked on to the line, its RE1-3 contacts open, the series
        string is broken, and power is removed from the L1 terminal
        of all other manual panels, disabling them. Latching con-
        tacts energize relay RE1 of the manual panel being placed
        on the line.
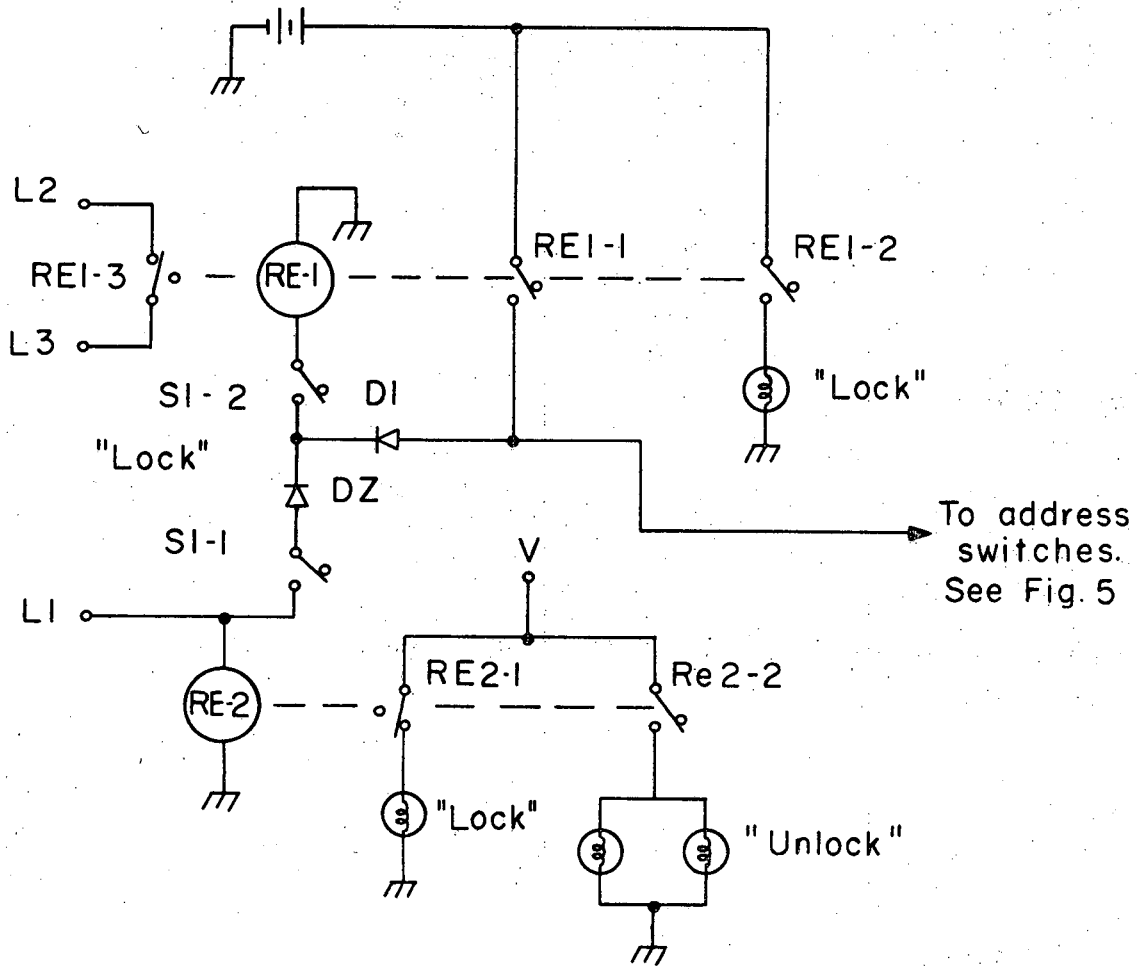
XBL692-1918

Fig. 4. Manual data-entry panel access logic. When any panel
is locked into the crossbar system, all RE2's drop out,
but only on the active panel does RE1 pull in. When it
does, contact RE1-2 puts power on the second "lock" lamp
of the active panel, thus providing an unambiguous in-
dication of which data-entry panel is activating the system.

When power is removed from the L1 line tie point, RE2 on all panels drops out, removing power from the two lamps labeled unlock and impressing power on one lock lamp through the normally closed half of contact RE2-1.

Note that when any panel is locked into the crossbar system, all RE2's drop out, but only on the active panel does RE1 pull in; when it does, contact RE1-2 puts power on the second lock lamp of the active panel. This scheme provides an unambiguous indication of which data-entry panel is activating the system, for if any panel is placed on the line, all manual panels have the power removed from both unlock lamps and power placed on one lock lamp. However, only the active data panel will have power put on both lock lamps. Contacts S1-2 are provided to unlatch RE1 when the manual panel is taken off the line. Lock-unlock pushbutton S1 is an alternate-action switch.

When a manual panel is activated, "battery" V, as well as latching RE1-1 on through contacts RE1-1, is connected to the common point of the address-selection switches as shown in Fig. 5.

Basically, each 0-9 address-selection button of each address decade, when pushed, impresses voltage on one crossbar address-relay coil. Actually, all manual panel address-selection buttons in the same "place", e. g., the 7 in the thousands decade, tie into a common bus line forming a large, expandable or-gate as new data-entry panels are added. A given manual panel may be locked out of some addresses by simply not connecting an address decade to the address bus.

The address-display section of the manual panel is conceptually simple (see Fig. 6). It consists of four Nixie tubes, a voltage for their common anodes, 10 conductor pairs from the primary crossbar address-display bus, and 10 pairs from the secondary crossbar address-display bus.
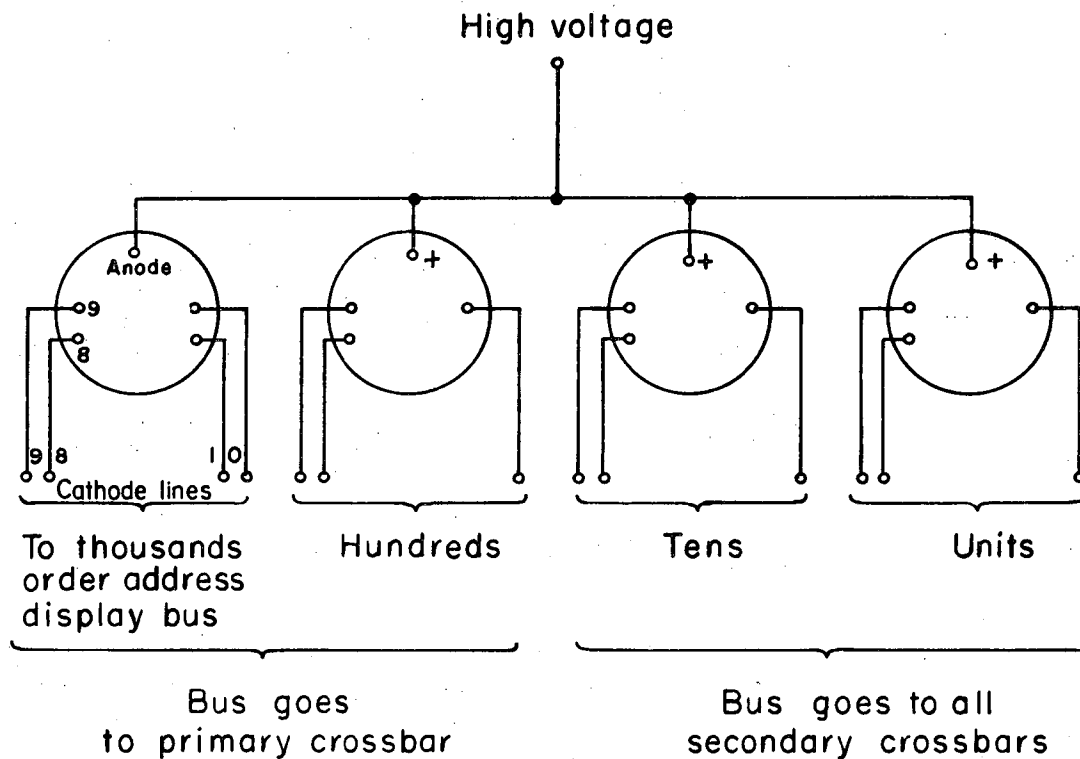
In operation, activation of a crossbar address relay coil causes one half of the cross-point addressing to take place, and also causes the closure of a set of contacts associated only with that relay coil. Each decade of the address display bus is then associated, one-for-one, with each decade of these special contacts (called off-normal pileups) such that, using our example, when any "7-in-the-thousands-decade" address button is pushed, the associated crossbar address relay is activated, closing its off-normal pileup and grounding the "7-in-the-thousands-decade" address display bus. The grounded bus line then causes every thousands decade Nixie-tube 7-cathode to glow.

To properly consider the data-entry section of the manual panel system (see Fig. 7), we must digress for a moment and discuss the actual sequence of operation of the system as a whole, considering its purpose. The operation sequence is as follows: The operator brings his manual panel into service by punching the lock button, providing of course that no other manual panel is already locked on the line. This enables his data-entry panel and disables all other panels. He may have previously selected the address of a remote terminal, or he may at this point punch in the address; the sequence is immaterial. The receiving device is not disturbed, even though selected, until the enter data button is punched, in order that the read back system (which is activated as soon as the address is selected) may observe
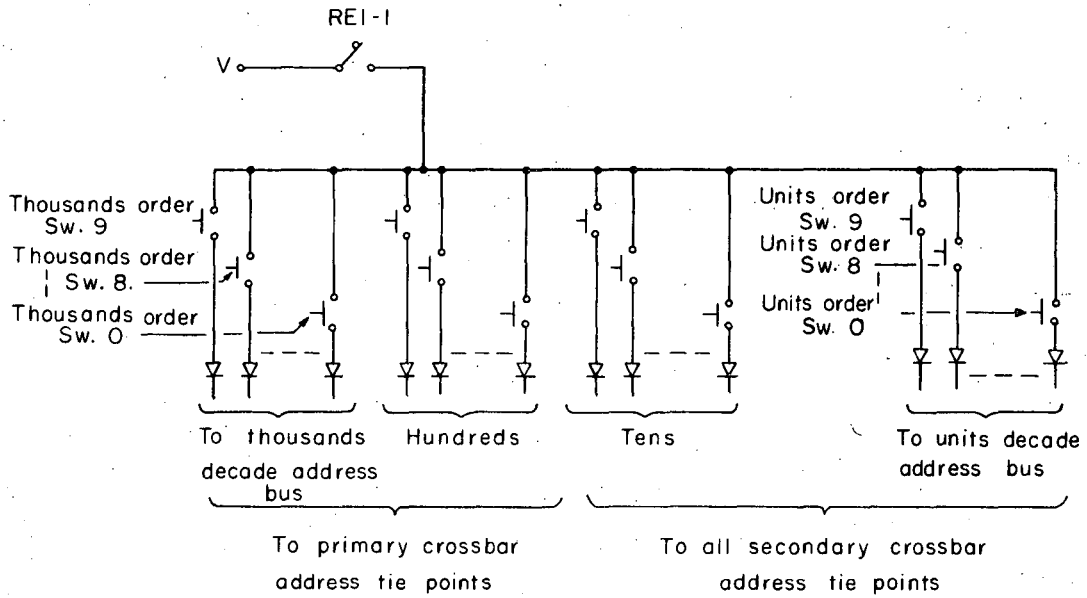
Fig. 5.   Manual data-entry panel address selection switches.
        RE1-1 permits only the excitation of the address key-
        board of the active panel.

High voltage

Anode

9
8

9 8   1 0
Cathode lines

To thousands   Hundreds   Tens   Units
order address
display bus

Bus goes   Bus goes to all
to primary crossbar   secondary crossbars

XBL 692-1920

Fig. 6.   Manual data-entry panel Nixie-tube address display.
         The Nixie-tube cathodes are grounded through the crossbar
         relays off-normal contacts.

To primary crossbar data input
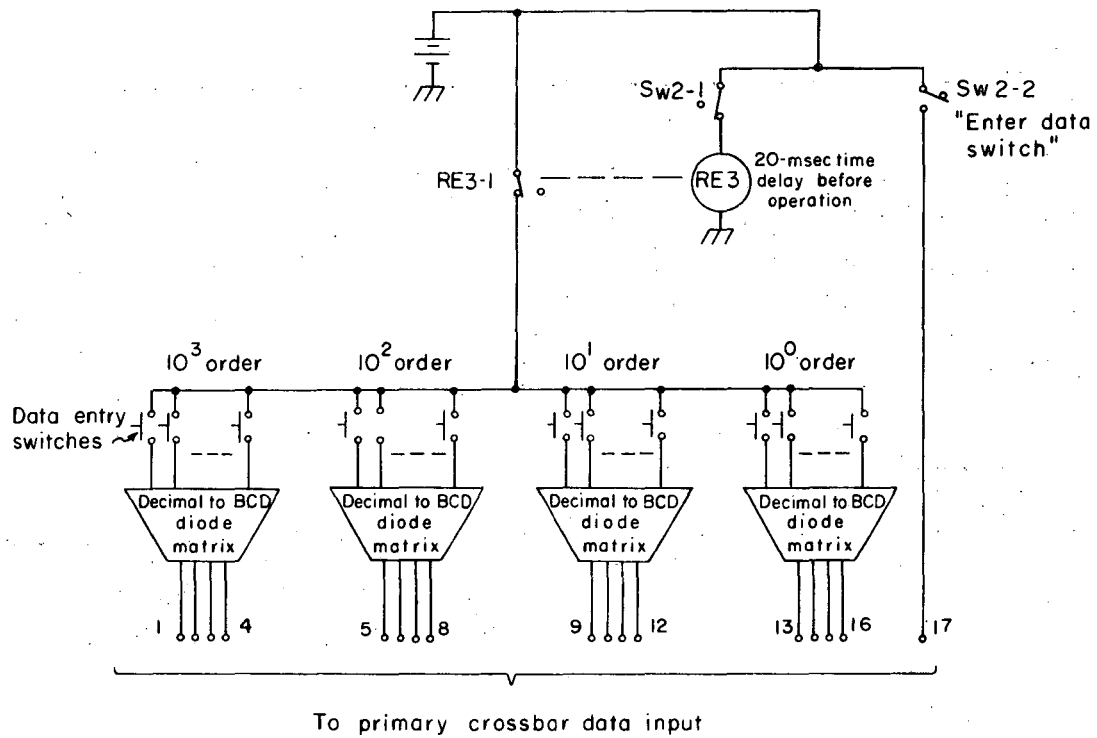
XBL692-1921

Fig. 7. Manual panel data-entry system. Diode matrices
       convert the decimal keyboards to binary logic.

the present set-point of the reference, giving the operator an opportunity to reset that value into his data-entry push buttons before punching the enter data button. In any case, as soon as the enter data button is pushed, the relay memory in the selected receiver is unlatched, i. e. , the latching contacts which lock each relay on or off are opened. During the enter data time of the manual panel operation, the relay memory in the receiver follows exactly the data entered in the data-entry decades section of the manual panel. If that information is changed, the relays in the receiver change. This mode of operation is useful so that the operator can, with a minimum of difficulty and extraneous actions, use the decade switches to tune the system controlled by the receiving device--almost as easily as he could tune by twisting a knob. When the set point has been selected and set into the receiver, the enter data button is pushed off, and power is immediately removed from line 17 of Fig. 13 allowing the latch relay in the receiver memory to drop out and provide latching voltage (through normally closed contact R17-1) to the latching circuit contacts of all of the 16 memory relays. Consequently, panel-selected on relays are latched on, others not. Twenty milliseconds later, the time-delay relay RE3 turns on, opening contact RE3-1 and removing power from the four decades of the data entry switches. Consideration of Fig. 7 also shows that, if through inadvertent action, lock unlock is pushed off before enter data is pushed off (unlocking the panel from the system), the desired sequence of actions is still executed correctly, and data are not lost.

Figure 7 shows that each 10-bit data-entry push-button decade is converted into four bits of binary coded decimal by the four encoding matrices. These are simply diode matrices converting 10-line input into four-line output. The diodes also act as the diode section of a large or gate, again enabling the data-entry switches of the manual panel to be decade-by-decade paralleled with the data-entry switches of every other manual panel.

Primary Crossbar

Before discussing the primary (or secondary) crossbar systems, one should mention that in this application, because of the rather large number of signal paths through each cross point to and from each receiver, it is necessary to parallel crossbars.

The succeeding figures indicate the circuitry for only two parallel primary crossbars, however it should be realized that this number can be two, three, four, or more, the only difference being that where two sets of contacts are shown in series in our twin-crossbar system, three would be in series in a triple system; where two contacts are paralleled there would be three in parallel, and so on for larger numbers of paralleled crossbars.

Addressing of one of the hundred possible cross points in the crossbars used in the present system is effected by selecting one of ten possible select magnets (vertical magnets) and one of ten possible hold (horizontal) magnets. The construction of the crossbar dictates that the select magnets must be energized and must settle to their steady-state position before the hold magnets may be energized. Figure 8 shows the primary crossbar address tie point where the 10 pairs of the primary crossbar address-selection bus terminate. The first 10 points of the tie point go directly to the ten select magnets; for instance RESA5 is the fifth select magnet on the A crossbar, RESB5 is the fifth select magnet on the B crossbar. The A and B
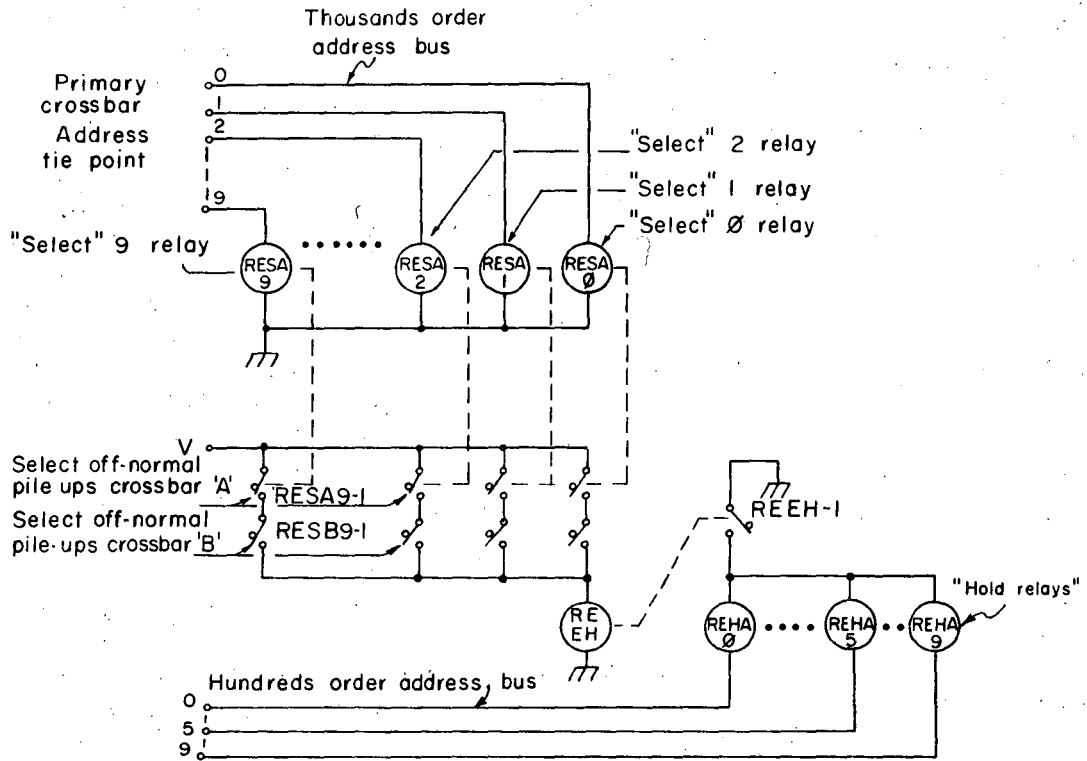
XBL692-1922

Fig. 8. Primary crossbar address selection. Select-coil
         off-normal contacts prevent excitation of the hold
   coils until the select coils are pulled in.

crossbars, as mentioned above, are functionally in parallel to provide twice the number of parallel paths through each crosspoint. Each select magnet has associated with it a set of contacts called the "off-normal pileups" (see Fig. 9). Closure of a select off-normal pileup contact indicates that the select magnet associated with it has been energized and also that the select bar associated with that off-normal pileup contact set has been fully closed. All of the normally open select off-normal pileup contacts in the primary crossbar set are paralleled, and the resulting or-gate used to energize the relay-enable-hold (REEH) relay shown in Fig. 8. Continuity through the contact or-gate set associated with REEH indicates that one of the select bars associated with the primary crossbar set has been energized and that there is a full closure of that select bar. Thus, the ten lines of the hundreds order of the primary crossbar address selection bus terminate at the tie point as before. Each tie point goes to one hold magnet, but the ground ends of all the hold magnets are tied together and run through a contact REEH-1 of the enable-hold relay; thus the hold section of the primary crossbar can not be energized unless the enable-hold relay has been energized, and it can not be activated until selection bars have completed their travel. The hold magnets were chosen to address the hundreds order (rather than the thousands), since normally the thousands order, the most significant order, is punched up first, giving time for the select bars to settle before the operator is ready to punch the hundreds order. (Typical enabling time for the selection bar is 40 msec).

Data entry section considerations in the primary crossbar are rather straightforward, since each individual crossbar simply acts as a hundred position, ten-pole switch.

The address display section of the primary crossbar set is shown in Fig. 9. Each address magnet, both select and hold, has associated with it off-normal pileups. The 20 lines of the address display bus are brought into the off-normal pileups such that when any select or hold magnet is activated, the associated pileup contact is closed and ground is impressed on one of the ten lines (per decade) of the address display bus. This then grounds one cathode of the Nixie tubes and displays a number. Note that the two paralleled individual crossbars have their hold and select addressing relays off-normal contacts in series for each position. That is, if address 9 in the hold (hundreds) is selected, both crossbar hold relays in the 9th position must be closed in order to get a ground on the address display line.
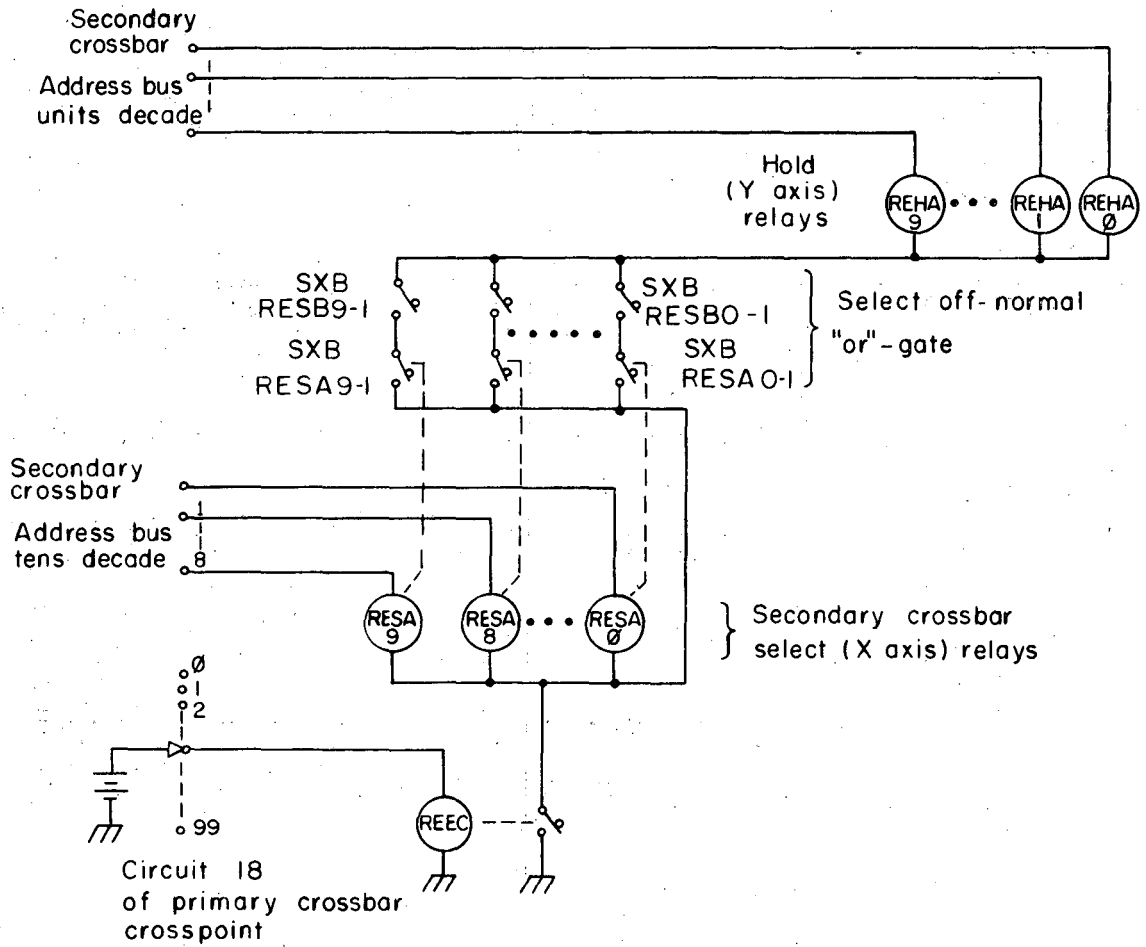
Secondary Crossbar

Address selection in the secondary crossbar varies only slightly in execution from the primary crossbar. There is, as before, a 10-pair address bus connecting all secondary crossbars and all manual panels. This 10-pair bus represents the units and tens positions of the address keyboard. Now in order to save power, if nothing else, it is desirable that only one secondary crossbar actually be operated by the voltage impressed on the address bus. Figure 10 shows a simplified diagram of the relay tree involved in the addressing of the secondary crossbars. As before, since secondary crossbars are also paralleled to handle the data flow, there are two relays shown in every case and two sets of contacts. The more significant addressing level, the tens place, as previously, goes to the select magnets; the units level goes to hold relays, since in this crossbar also the
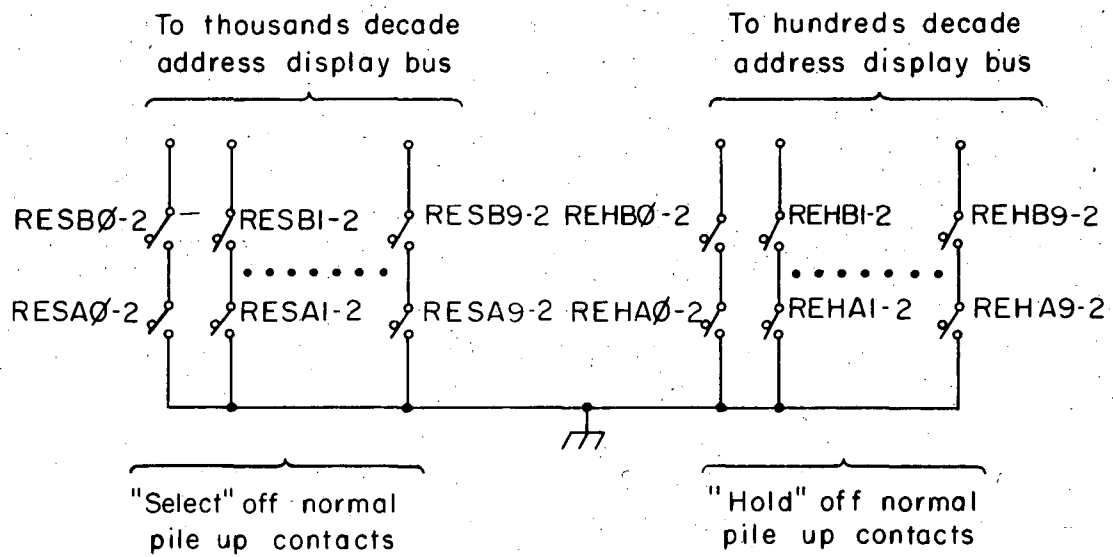
Fig. 9.   Primary crossbar address display.

XBL692-1924

Fig. 10. Secondary crossbar addressing.

select magnets have to be energized before the hold magnets may be. The ground ends of all hold magnets are tied together and run through an or-gate consisting, as previously, of all the select off-normal pileup contacts. Two contacts in each place are shown in series since both crossbars must have finished their selection process before the hold magnets may pull in. Then the bottom end of the select relay tree and the hold relay tree are tied together and run through to a relay contact associated with the enable crossbar relay, REEC. This relay is conditioned by a voltage brought through one channel of the primary crossbar crosspoint which references the particular secondary crossbar of interest. Thus voltage (or no voltage) from the 10-pairs of the secondary crossbar address bus is impressed on the top end of all the select and hold magnets of all the secondary crossbars, but only one secondary crossbar will have its REEC "on" (enabling address relays), since only one crosspoint on the primary crossbar could have been selected.

Address display in the secondary crossbar system is similar to that in the primary crossbar system. A 10-pair "ground-for assertion" bus connects all manual panels to all secondary crossbars. When a particular address is chosen in the secondary crossbar, two of the 20 lines (one in the select decade and one in the hold decade) will be grounded through the off-normal contacts. Since this line ties all Nixie number cathodes together for all Nixie tubes of a given "place" on all manual panels, all of a particular Nixie number will be illuminated.

Figure 11, for example, shows two lines of the 20-line secondary crossbar address display bus, in particular the select 7 and hold 3 magnet lines. It shows that on all of the secondary crossbars the two off-normal pileups for the select 7 magnet are connected in series to the select 7 (tens place) address display bus. This bus then goes in parallel to all of the 7 grids in the tens-place Nixie tube for all the manual panels. Similarly, the other bus line shown indicates when it is grounded that one of the secondary crossbar parallel pairs had had its 3 hold (units-place) magnet excited and the two off-normal pileups for the 3 hold magnet have closed in series grounding the 3 units bus. This bus then causes the 3 grid of the Nixie tube in the units place in all of the manual panels to glow.

The data transmitted through the secondary crossbar out to one of the hundred possible receivers connected to the particular selected secondary crossbar pair consists of 17 lines; 16 bits worth of four decades of binary-coded decimal information, and one bit used to latch/unlatch the relay memory in the receiver.
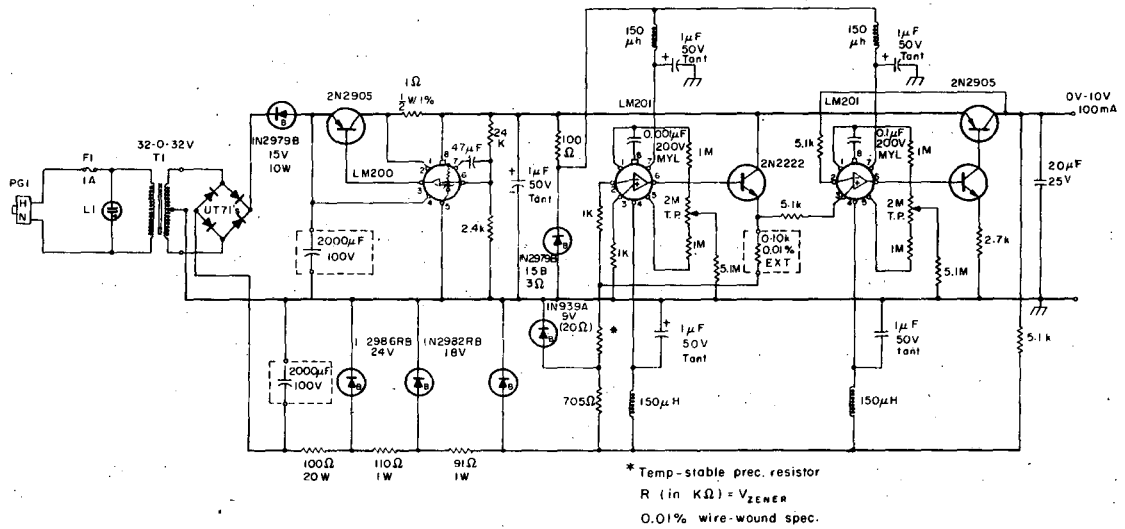
Reference Power Supply

For regulated systems such as magnet power supplies and servo systems, the receiver consists of a digitally operated reference power supply. The schematic, Fig. 12, should be perused for an appreciation of how the data-transmission system described above produces its effect.

The reference power supply consists of a positive and a negative 1% regulated power loop, a 0.01% current-control loop and a 0.01% output-voltage control loop. The negative 1% regulated power loop consists of the 24-, 18-, and 15-V Zener. The positive 1% power loop consists of the pass

Address display bus (tens place)

Address display bus (units place)
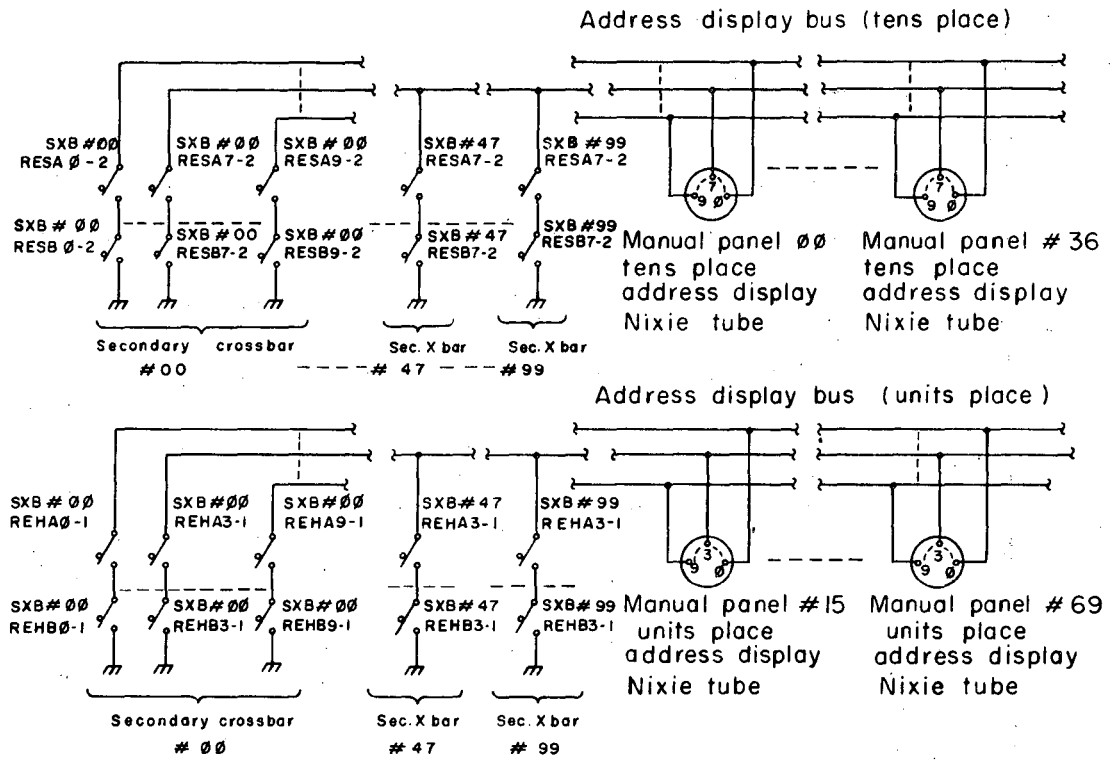
XBL692-1925

Fig. 11.   Secondary crossbar address display.

Fig. 12. Precision regulated programmable-reference power
          supply. The output voltage is adjustable from 0 to 10 V
          in 1-mV steps.

transistor Q1 and preregulator Q2 (LM200), and the associated voltage-division resistors.

The 0.01% current string comprises R3, D1, R5 and Q3 and Q4. The 1N939A is a 9-V temperature-compensated reference Zener. Resistor R3 is chosen so that its resistance in kilohms is equal to the precise voltage of the 9-V reference Zener. Thus, if the voltage at the top of R3 (at the junction between R3 and R4) is held at 0 V, precisely 1 mA flows through R3 and consequently through R4. The virtual grounding of the junction is insured by the amplifier loop of Q1, Q2, and R4. Thus, the resistance of R4 in kilohms will be reflected as the voltage at the junction of R4 and Q3 (because of the virtual grounding of the junction between R3 and R4). This voltage at the top of R4, is sensed by Q5, compared with the output voltage of the power supply, and the loop of amplifier Q5, Q6, and Q7 modifies the drop across the pass transistor Q7 to insure that the output voltage does agree with the voltage at the top of R4 regardless of load conditions.

The resistor string R4 is shown in more detail in Fig. 13. It is actually 16 resistors in series, each being normally shorted by a normally closed contact on one of the 16 relays. The range 0 to 10 V is desired at the power-supply output, consequently the resistor string is a four-decade, 1-2-4-8 ratio string. If a relay is selected and energized, its resistor-shorting contact will open, allowing an incremental voltage drop across the R4 string due to the constant 1-mA current through the R4 string.

The mechanism of data entry can be best seen by referring to Fig. 7 and Fig. 13. When the manual panel enter data button is pushed, relay 17 is energized. This removes voltage from the latching circuit of each of the data memory relays, allowing them to follow immediately the changing voltages on the 16-input lines. This correspondingly changes the set of resistors chosen to represent R4 and consequently changes the output voltage of the power supply. When the operator punches the enter data button to off, voltage is immediately removed from RE17, causing it to relax closed and to energize the latching circuits in the 16 data-memory relays. Thus, those that were energized at the time enter data was punched off will remain energized, and those which were not energized will not be energized. After 20-msec delay (from the time-delay relay mentioned in the manual panel discussion), the voltage is removed from the manual panel data-entry switches, and the power supply remains completely detached and locked to the set point until such time as the operator desires to enter new data.

Numerically Operated Contactor

This device is intended to permit control of remote on-off equipment such as power supplies, filament transformers, blowers, and pumps. The basic circuit is shown in Fig. 14. Four such circuits can be built on a common panel; each panel is addressed by the address keyboard of the control panel. The data relays are connected to the data keyboard in a manner similar to the digital reference. The circuit is arranged to convert binary-coded decimal data to decade data. Relays 10 through 19 are control relays. The hundreds and thousands columns can be used to turn on equipment, while the units and tens columns can be used to turn it off. The control relays can be connected to operate equipment directly, providing control of twenty devices, or the control relays can be connected to the select and hold coils of

Inputs to reference voltage supply from secondary
crossbar switched crosspoint
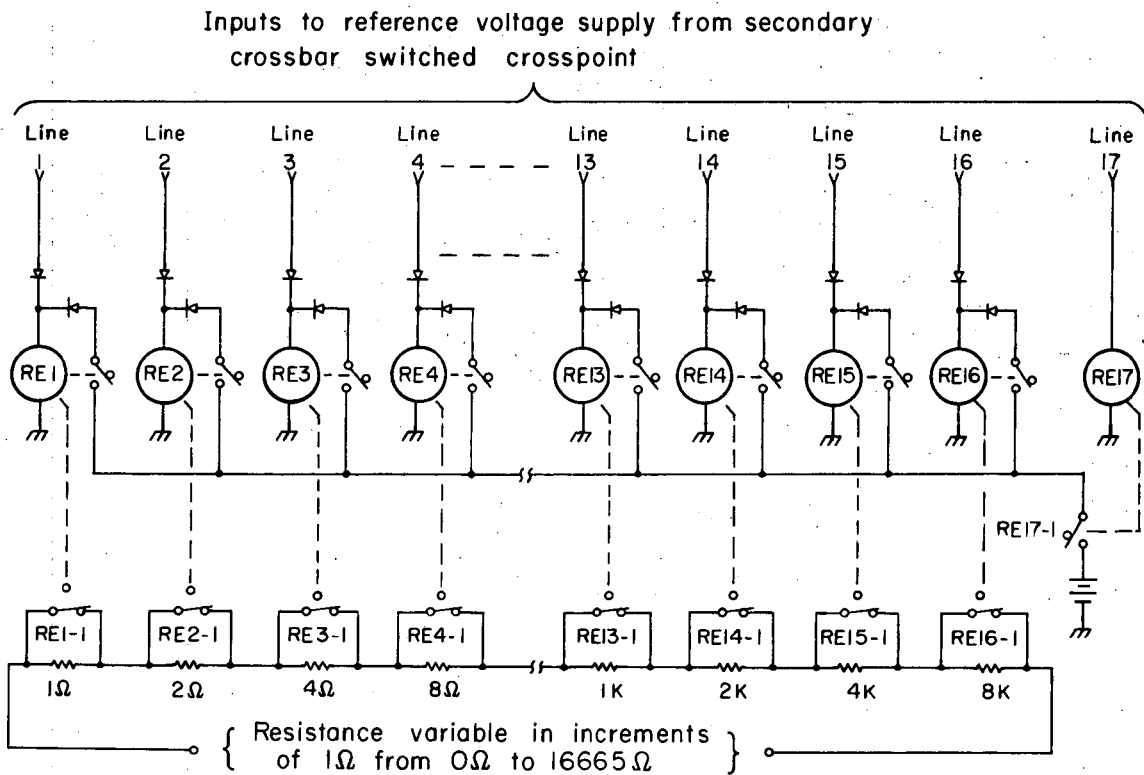
XBL692-1926

Fig. 13. Reference-voltage supply detail relay-switched
resistor string. This circuitry is a part of the
reference supply. The relays provide extremely
high noise isolation between the control system and
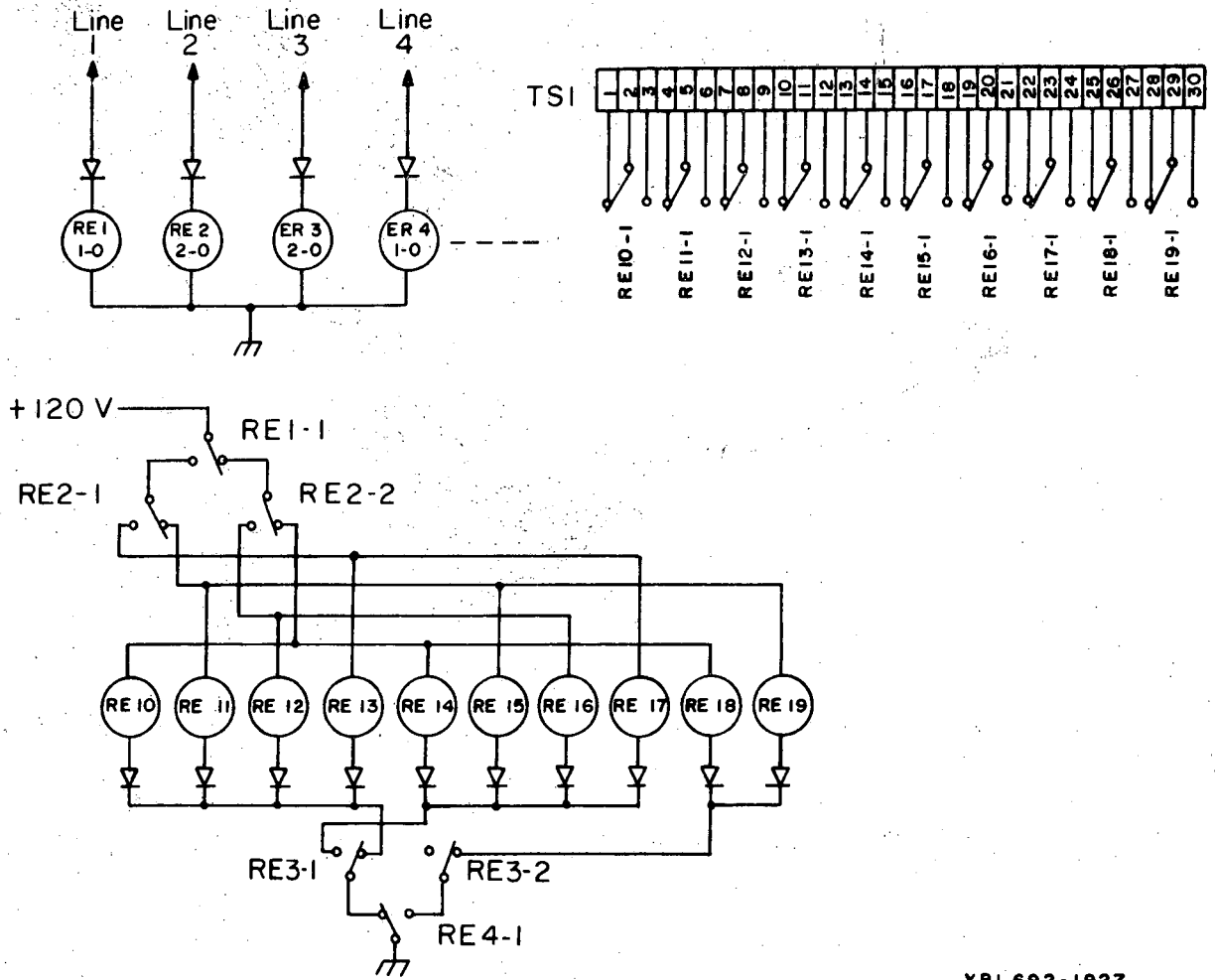the precision reference voltage.

Fig. 14.   Basic circuit of numerically operated contactor.
          Four such circuits are included on each panel.
          Control relays RE10 through RE19 actuate any
          on-off-type equipment.

a pair of crossbar relays providing on-off control of a hundred pieces of equipment by each panel. The numerically operated contactor uses only eight conductor pairs of the crossbar system, so those remaining are available to bring back status information of the controlled equipment.

Computer Integration

Examination of the figures that relate to "manual panel" operation will indicate how the computer is easily integrated into the system to simulate another manual panel. Since the system is entirely digital, the computer integration demands only simple input level changes, output level amplifiers, and either external hardware or internally generated time delays (of known duration) to allow for relay settling.

One automatic operation mode is record and reproduce. In this mode, after the accelerator has been tuned, the computer manual panel sequentially cycles, and, using the read-back system and a digital voltmeter, records all manually set reference set points, storing them in memory and on magnetic tape. Later if it is desired to reset the accelerator to the previous configuration, the applicable magnetic tape can be pulled, read, and the computer manual panel used to automatically set (and check) each receiver.

Equipment Installation

Relay installation techniques have been highly developed by the telephone companies. We should follow their practices. Where exposed contact relays are used, care should be exercised to minimize the presence of dust. Concrete surfaces can be given a coat of high-gloss enamel, floors can be covered with linoleum. The room can be kept at a positive pressure with filtered air. Relays can be mounted with the contact-making surfaces vertical. The dust covers, supplied with crossbar relays, should be installed and the racks should be designed to be as dust-tight as possible.

Multipair cable, which is made in sizes up to 51 pairs, is economical and can be used for interconnection between crossbar relays. Number 22 wire is convenient for soldered connections and No. 24 for wire wrap. Small-diameter coaxial cable can be used for short distances near the crossbar relays where cable density is high, but should be connected to matching low-loss cable for the long runs.

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