The Digital Voltmeter — An Inside Story

"Quality Control is Everyone's Business at NLS"

This handbook is intended for anyone who wishes to understand how digital voltmeters work.

Originator of the Digital Voltmeter

NLS non-linear systems, inc.

DEL MAR, CALIFORNIA

Phone SKyline 5-1134 TWX: DEL MAR 6-345

The Digital Voltmeter — An Inside Story

"Quality Control is Everyone's Business at NLS"

This handbook is intended for anyone who wishes to understand how digital voltmeters work.

1st Edition, 1963

INTRODUCTION

Digital voltmeters, unlike moving-needle voltmeters, display their measurements in a row of numerals. The digital voltmeter with its direct reading capability, virtually eliminates human error in interpretation since the position of a needle on a calibrated scale need not be read. However, simple voltage representation is not adequate unless the increment displays available are so close as to make it possible to discriminate from among tiny voltage differences. For many applications, the ability of a digital voltmeter to discriminate whole volts is often sufficient. Beyond this, if the digital voltmeter is capable of displaying tenths of volts, this is all to the good. Best of all is the modern digital voltmeter which can measure and display voltages as small as one-thousandth of a volt, or, in the case of five digit instruments, one ten-thousandth of a volt. Such fine measurements, of course, cannot be made with ordinary moving-needle voltmeters. In addition to being able to measure such fine voltages, modern digital voltmeters are capable of rendering readings in a fraction of a second. Some instruments will read even faster than one ten-thousandth of a second after the input signal has been applied. Speed in itself, though, doesn't mean much except for those users who need to observe or record rapidly fluctuating voltages.

As can be seen, the old fashioned moving-needle meter is not able to keep up with an increasing demand for close and rapid voltage measurement; the digital voltmeter therefore fills an essential need in applications requiring high speed, accuracy, and sensitivity.

Because of its many capabilities, the modern digital voltmeter is a complex instrument, one which can be approached only by taking first things first. Thus, the opening chapter presents, in its most rudimentary form, the potentiometer principle. Succeeding chapters build carefully upon this base so that meaningful descriptions of actual instruments may be offered.

The instruments described are manufactured by NLS. Chapter II explains the operation of the Industrial Series Instruments, with special emphasis upon the Model V64A, the least complex instrument in the Series. Chapter III describes the NLS Series 30 Digital Voltmeters.

Contents

Chapter I

Applying the Potentiometer Principle

Figure 1 illustrates a basic potentiometer circuit, the basis of most digital voltmeters. As shown in the figure, an unknown voltage can be determined by simply adjusting the voltage divider until the reference voltage is equal to the unknown voltage. In this figure, the galvanometer indicates zero current flow when electrical balance exists. The voltmeter then indicates the voltage at balance. Note that when a zero condition exists, there is no load on the voltage being measured. That is, when two voltage sources "face" each other, with positive meeting positive and negative meeting negative as shown in Figure 1, there is zero current present if both voltages are identical.

In order to produce a digital voltmeter which is capable of indicating voltages at a millivolt or sub-millivolt level, some means of amplification must be used. A conventional practice is to sample the unknown voltage with an electro-mechanical chopper so as to produce an AC signal which may be readily amplified. Such a chopper circuit is shown in Figure 2.

Basically, a chopper is a single-pole, double-throw switch which, in this application, is actuated by an electro-magnetic coil assembly connected to a 60-cycle source. As shown in Figure 2, the chopper arm swings between the unknown input voltage and the reference voltage, generating a voltage wave form at the chopper arm. This wave form is a 60-cycle square wave whose peak-to-peak amplitude is the difference between the unknown voltage and the reference voltage. A series of wave forms is shown in Figure 3. This figure illustrates the chopper output under various conditions of input voltage and reference voltage. Any difference between these two voltages results in an AC signal which feeds the amplifier. Figure 4 illustrates an elementary self-

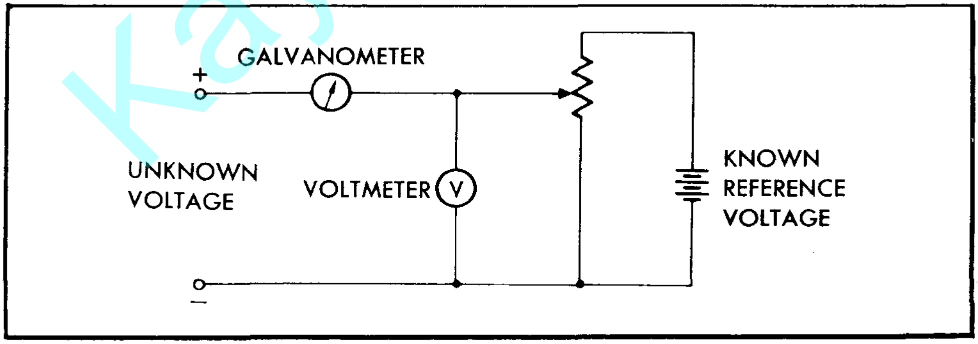

Figure 1. Basic Potentiometer Circuit.

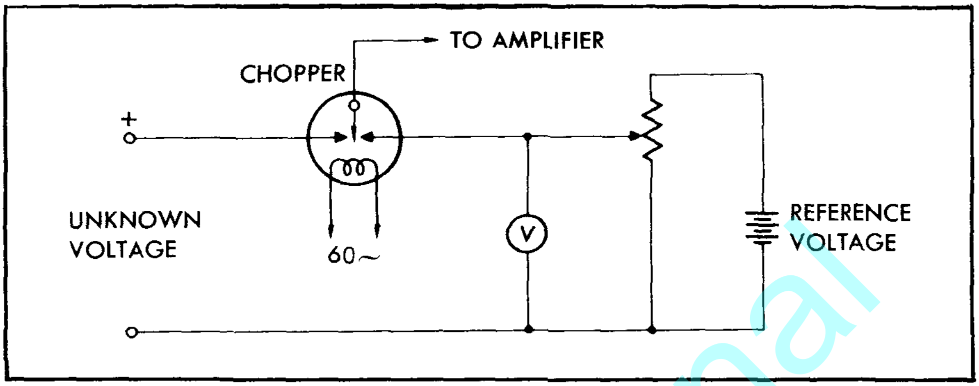

Figure 2. Basic Potentiometer Circuit with Chopper.

balancing potentiometer, or digital voltmeter, using a chopper and an amplifier. The reference voltage is applied to a voltage divider which has been assembled around a 10-position rotary stepping switch. The switch arm is "stepped" around these 10 positions by pulsing the stepping-switch coil with the amplifier output. An additional switch arm is ganged to the divider arm so that both may be driven by the same stepping mechanism. This second arm has its own set of contacts which are used to select and illuminate the correct readout lamps under the appropriate readout numerals. Each numeral, 0 through 9, corresponds to the voltage present at the switch arm of the voltage divider.

To observe the operation of the elementary digital voltmeter shown in Figure 4, assume that any voltage in one-volt steps, from 0 to 9 volts, is applied as the unknown input. Also assume that one volt or more is sufficient to drive the amplifier which, in turn, drives the stepping switch. When these conditions occur, the following facts become evident:

- With any input from 0 to 9 volts, only one position on the reference voltage divider will match the input voltage.
- All other positions will produce a voltage output of one volt or more at the chopper arm. This is sufficient to drive the amplifier and the stepping switch.

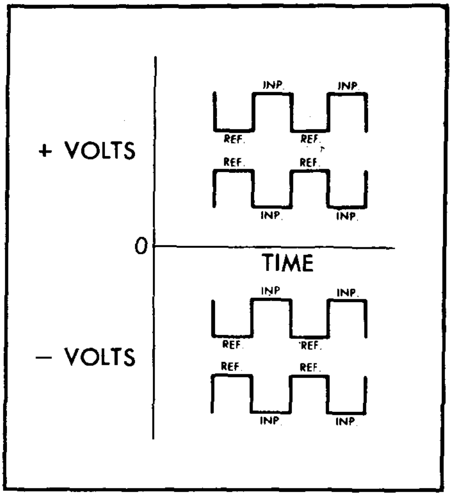

Figure 3. Chopper Wave Forms.

- The stepping switch will receive one pulse for each full swing of the chopper arm as long as a difference exists between the unknown input voltage and the reference voltage.
- When the reference voltage divider output equals the unknown input voltage, no output is developed at the chopper arm, and the amplifier ceases to operate the stepping switch.
- The second section of the stepping switch connects to a specific readout lamp when balance is reached. An appropriate numeral is illuminated, which corresponds to the reference voltage divider tap, and therefore corresponds to the unknown voltage.

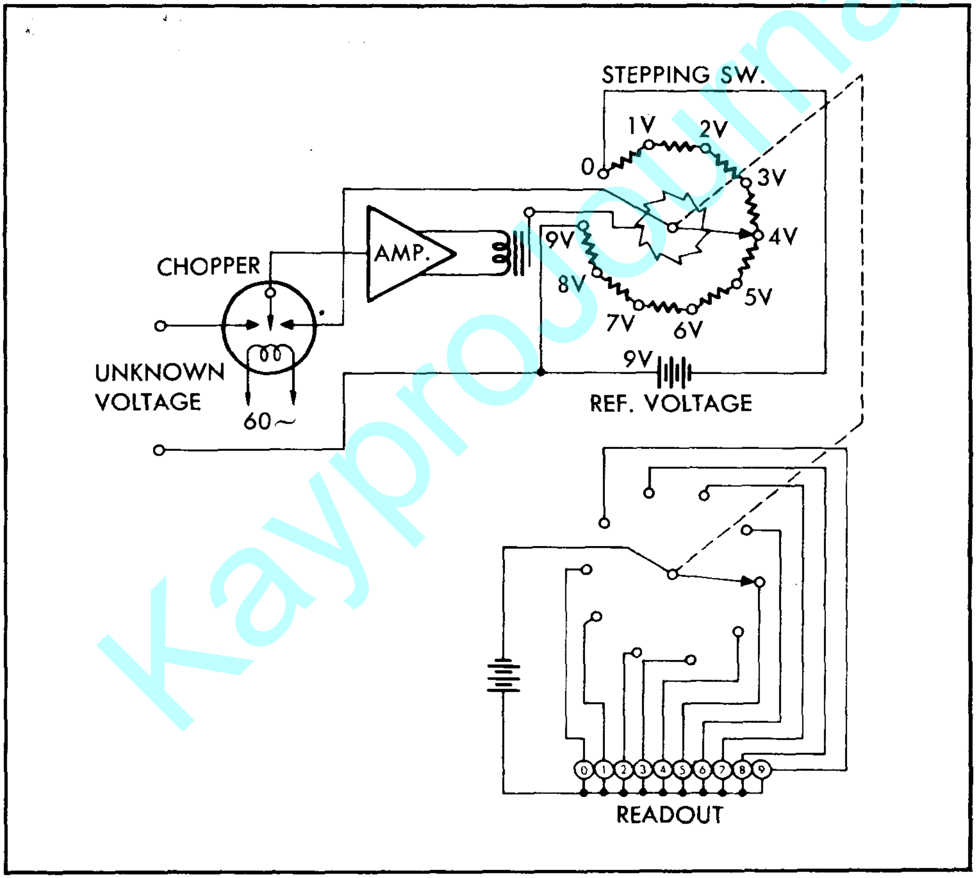

Figure 4. An Elementary Digital Voltmeter.

Chapter II

A Rudimentary Digital Voltmeter

Although the simplified circuit shown in Figure 4 illustrates the principle upon which a digital voltmeter works, considerably more sophisticated circuitry is required to produce a practical instrument. In order to present a detailed description of a working instrument, the following discussion is based upon the specific circuit used in the NLS Model V64A. This instrument is fairly simple, and does not have automatic ranging or automatic polarity-indicating features. Instead, it uses front panel controls to establish range and polarity.

Bringing the elementary instrument shown in Figure 4 up to the realm of practical application, a number of circuit additions and modifications need to be incorporated. First of all, the elementary circuit shown in this figure cannot measure an input voltage of reverse polarity unless the reference voltage is also reversed. Secondly, like all voltmeters, the digital voltmeter requires a range multiplier to extend its useful range. Thirdly, the chopper must be protected against inadvertent application of excess voltage.

Figure 5 shows the circuit changes made to meet these requirements. A polarity reversing switch has been added to reverse the reference voltage; an input voltage divider and range switch have been added to extend the voltage ranges by ten times and a hundred times; also, a neon lamp and limiting resistor have been added to protect the chopper against accidental high-voltage inputs.

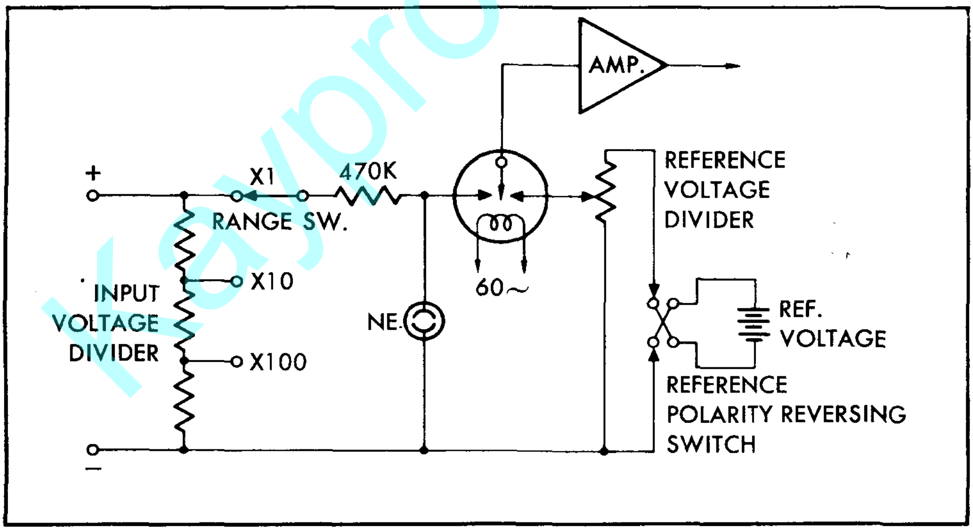

Figure 5. Range and Polarity Switching with Chopper Protected by Resistor and Neon Lamp.

1. The Reference Supply

Any practical digital voltmeter must contain an extremely stable voltage source for reference purposes if the instrument is to be consistently accurate over long periods of time. Also the voltage divider must be capable of being set to very fine voltage increments. Figure 6 shows a typical reference supply used in digital voltmeters. A power transformer supplies AC to a full-wave bridge rectifier. This rectified voltage is then filtered through a two-section RC filter. The voltage at the filter output is regulated by a gas-type voltage-regulator tube which, in turn, feeds a pair of matched zener diodes. These diodes are of equal and opposite temperature coefficients, and are located in a crystal oven which holds the temperature within plus or minus ½ degree, Centigrade. With this method, stability is better than one part in ten thousand over long time periods.

2. The Kelvin-Varley Voltage Divider

To obtain the precise increments in voltage required of the voltage divider, a modified Kelvin-Varley type voltage divider is used. With this modified divider the value of each decade resistor is the same, thus permitting each decade along with its stepping switch to be made into interchangeable plug-in units. Since all decades are interchangeable, production, trouble shooting, and replacement are simplified.

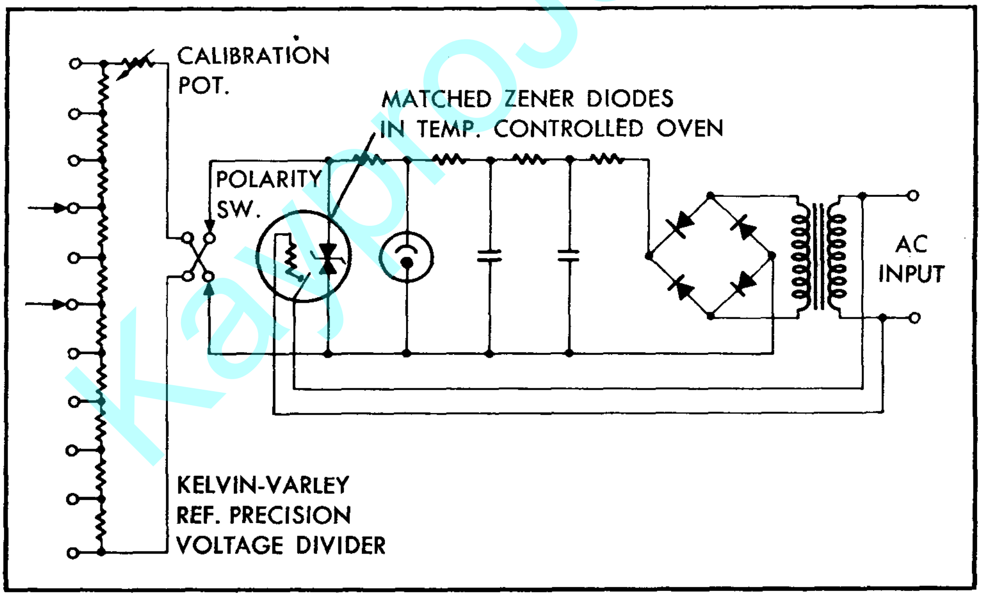

Figure 6. Reference Power Supply.

As shown in Figure 7, each decade consists of eleven 5,000-ohm resistors. The output of the decade is selected by a pair of switch arms across two adjacent 5,000-ohm resistors. The switch arm feeds the next decade of 55,000 ohms, and is shunted by a 12.5K ohm resistor. A quick calculation will show that the 10K ohm output shunted by the 12.5K ohm resistor, and by the following 55K ohm decade, equals 5,000 ohms. Under these conditions, the switch arms will select exactly one tenth of the voltage present across each decade.

By tracing the output of the reference voltage supply into the Kelvin-Varley divider, it will be seen that the voltage output of the most significant decade (on the left) appears across a pair of switch arms. These arms "bracket" a one-volt region of the reference voltage. Once the desired voltage has been bracketed, it is passed on to the following decade which again brackets the voltage, but this time to within one tenth of a volt. The third decade is now able to select a desired voltage within one hundredth of a volt. Finally, in the fourth decade, a voltage can be selected in the millivolt region. In Figure 7, the ten-volt reference has been bracketed down to produce a voltage of 4.321 volts.

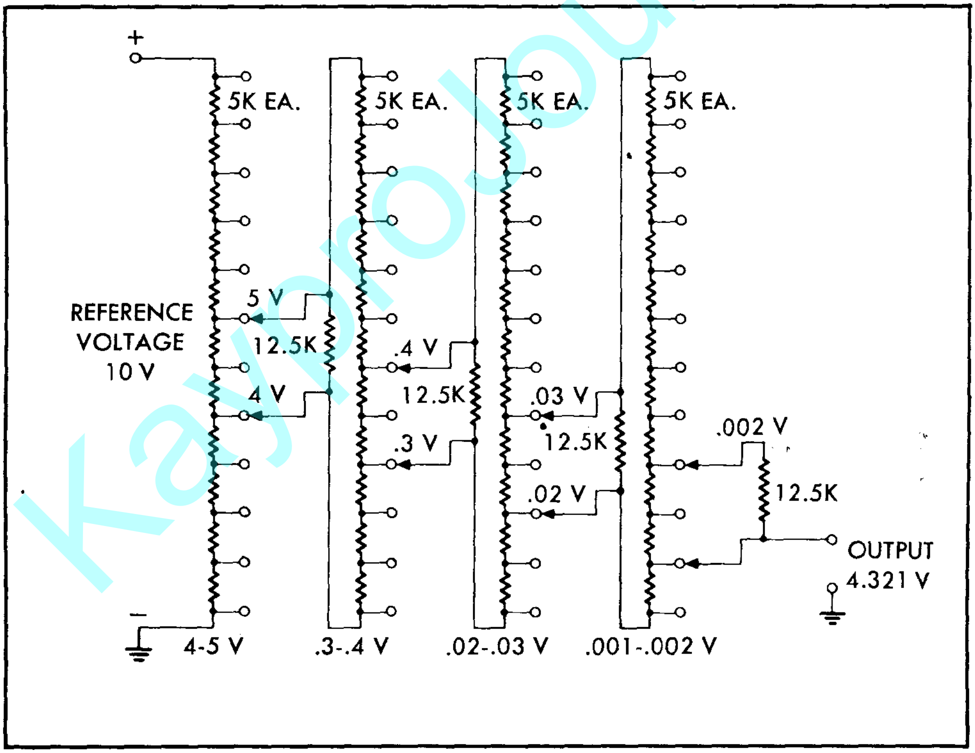

Figure 7. Modified Kelvin-Varley Voltage Divider.

3. The Voltage Amplifier

It can be seen from the foregoing discussion that an amplifier is needed to balance out voltage increments which are on the order of one millivolt. Figure 8 shows a typical high-gain three-stage amplifier with a phase-inverted output. As shown also in this figure, the chopper arm swings between the input terminal and the Kelvin-Varley voltage divider output, thus generating a square wave form as previously described. Note that the square wave may have either a positive- or a negative-going polarity, depending upon whether the input signal is of higher or lower potential than the Kelvin-Varley divider output. The square wave output is applied to a cathode-coupled amplifier stage, designed to preserve the square wave form and, at the same time, minimize input circuit drift. The second stage is also a cathode coupled stage which has a variable resistance coupling between its two cathodes. A front-panel control is ordinarily provided to adjust the digital voltmeter sensitivity. An overall amplifier gain adjustment is provided at the plate of the second amplifier to compensate for variations in tube and amplifier gain. Phase inversion is required to develop a pair of amplifier output signals which are directly related to the polarity of the original square wave output of the chopper. This pair of signals is used by the instrument to determine whether the Kelvin-Varley divider is to be driven "up" or "down" in order to seek a balance.

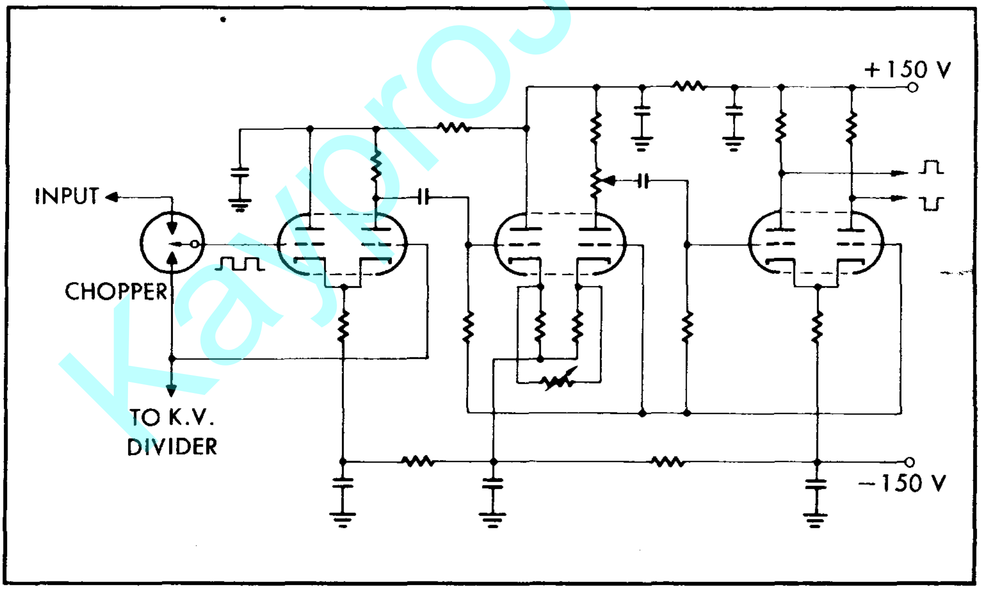

Figure 8. Voltage Amplifier Used to Drive the Thyratrons.

4. A Complete Digital Voltmeter — Manually Operated

Up to this point in the discussion, we have been systematically assembling a fundamental digital voltmeter. Figure 9 integrates the material covered and shows an instrument at the present stage of the discussion. As can be seen, we now have a practical instrument, one which can be operated with manual controls so as to provide highly accurate readings. By observing the amplifier output wave form with an oscilloscope, we can determine if the unknown signal is higher or lower than the Kelvin-Varley divider output, and adjust the four decades of the divider so as to produce a nulled output. If the output signal reduces but cannot be nulled out when the divider output reaches zero, then the reference polarity must be reversed to balance against the input. On the other hand, if the amplifier output is reduced but not nulled out when the Kelvin-Varley divider is at max-

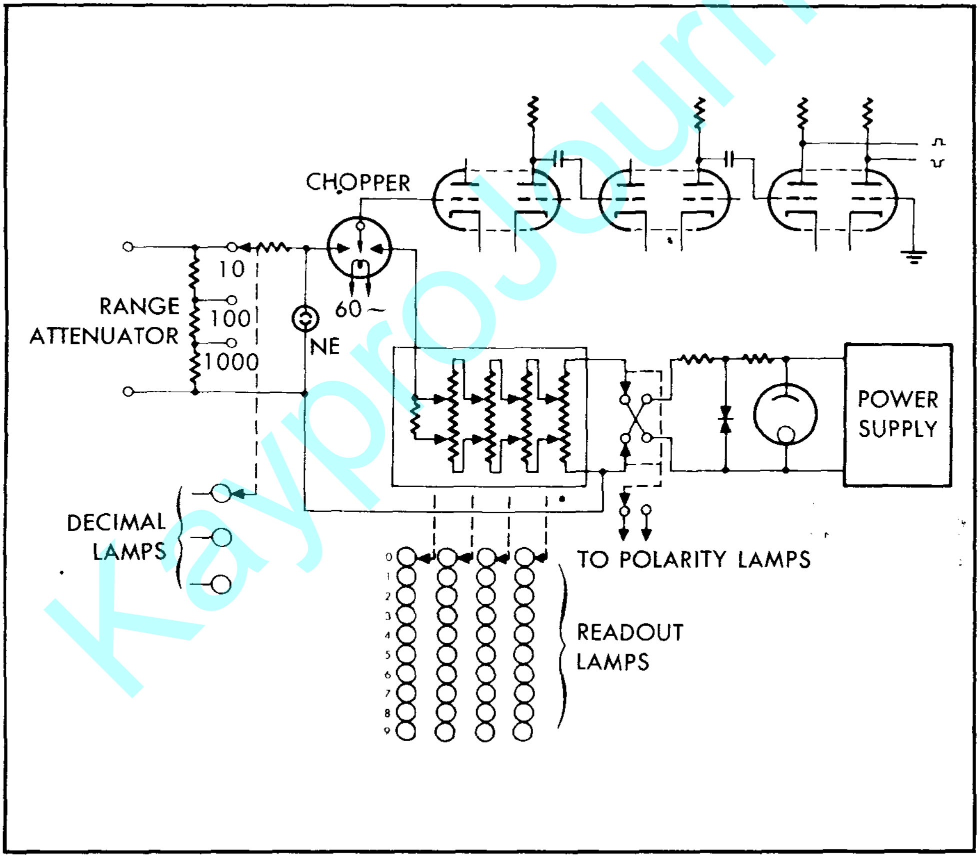

Figure 9. A Manually Operated Digital Voltmeter.

imum, then the input signal is greater than the reference voltage, and the input divider must be brought into action with the range switch. The Kelvin-Varley divider is then readjusted for a null. The readout lamps are wired to ganged switch sections operating with each Kelvin-Varley decade. Plus or minus polarity is indicated by operating similar plus or minus readout lamps also ganged with the polarity switch. The proper decimal points are indicated by decimal readout lamps ganged to the range switch.

5. A Complete Digital Voltmeter — Automated

In order to automate this simple digital voltmeter, all that is needed is to make use of the amplifier outputs to drive the stepping switches. Since considerable power is required to drive stepping switches, only a very few types of electron tubes are suitable as drivers. The type 2D21 miniature thyratron lends itself well to this purpose.

Figure 10 illustrates circuitry from the amplifier outputs to the thyratrons which drive the stepping switches. Note that the thyratron tubes operate from an AC plate supply, thus simplifying power supply design and automatically extinguishing the thyratrons after each conducting period. A series of wave forms is shown in Figure 11. These indicate the timing relationships of the circuits from the phase inverter outputs to the final stepping-switch output pulses.

The stepping switch drive circuit consists of a pair of small thyratrons, V6 and V7, which are actuated by the phase-inverter outputs, and which in turn trigger V8 and V9, the stepping-switch driver.

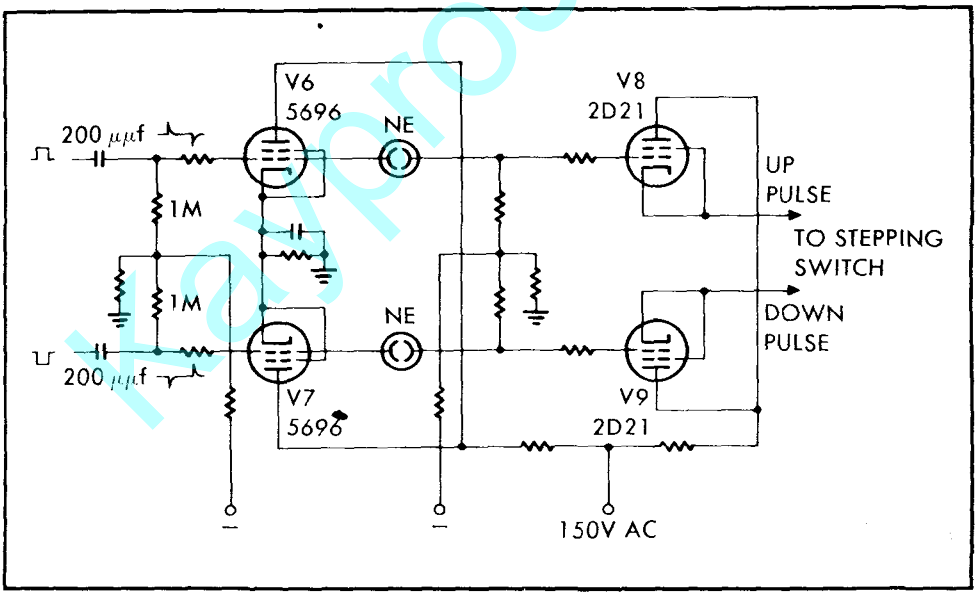

Figure 10. Thyratron Stepping-Switch Drivers.

These thyratron circuits operate as follows:

The square-wave outputs of the phase-inverter stage are coupled through 200 mmf capacitors. This value, in conjunction with the following 1-megohm resistors, differentiates the square waves, thus producing positive pulses corresponding to the leading edges of the positive-going square waves, and negative pulses corresponding to the trailing edges. This pulse polarity is inverted when the square wave is inverted as shown in Figure 11. These differentiated pulses are then applied to a pair of 5696 thyratrons, V6 and V7. V6 and V7 are normally biased to their cut-off points by a resistive divider. In Figure 10, the positive differentiated pulse turns V6 on, while the negative pulse applied to V7 has no effect. With V6 turned on, a large current flows through R, the common cathode resistor for V6 and V7. The voltage drop across R charges C, connected across R, and also puts V7 further into the cut-off state. Once V6 is turned on, it remains on until AC plate voltage returns to zero at the end of the positive half cycle. V6 and V7 would normally be ready for another cycle of operation every 60th of a

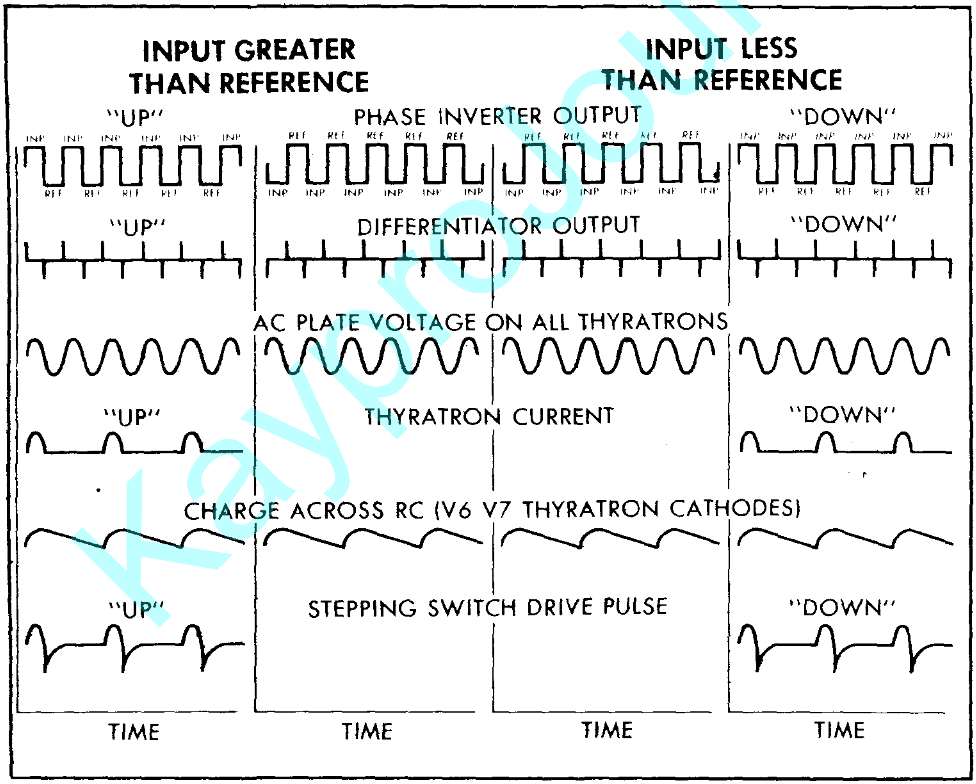

Figure 11. Timing and Phase Relationship of Inverter and Thyratrons.

second except for the time constant designed into C and R. C and R are proportioned to hold V6 and V7 in a cut-off condition for a full AC cycle after either V6 or V7 has fired. This is done to provide a frequency halving action, so that the power thyratrons and the stepping switches operate at a 30-cycle rate.

V6 and V7 drive the output thyratrons in a novel manner. When either V6 or V7 fires, the ionized interior of the tube creates a low impedance conducting path from the plate to the control grid. The resulting voltage pulse at the control grid turns on the neon lamp which is coupled to the 2D21 output thyratron. The 2D21 switches on, passing a large current sufficient to operate the stepping switch. Current-limiting resistors are used in the thyratron plate circuits to prevent excess plate current flow through the thyratron.

6. The Stepping Switches

Stepping switches operate mechanically in one direction as shown in Figure 4. When the electromagnetic driving mechanism is energized, an armature is pulled toward the coil against the force of a helical spring. This action cocks the switch, but does not advance the contacts. When the electromagnet is de-energized, the helical spring returns the armature to its original position. This return movement operates a ratchet so that the rotary contacts will advance one step. In this way, switching occurs only after the electrical noise of the driving current has ended; thus the return spring rather than driving current advances the contacts. When the last switch position has been reached, the next pulse advances the switch to the first position again, and additional pulses cause the stepping switch to repeat this cycle.

Both "up" and "down" pulses operate the stepping switches in the same mechanical direction of rotation. The manner in which these pulses are routed through the stepping switches determines a sequence of operation which allows a balance to be reached in a minimum number of steps. Both "up" and "down" pulses are usually required to achieve a balance, and several decks of switches are needed to route "up" and "down" pulses.

7. Stepping Switch Pulse Circuits — Up Pulses

To follow the operation of the stepping switches and the pulse switching circuits, assume that all switches are resting at zero as shown in Figure 12. With the switches in this position, there is no output from the Kelvin-Varley divider, and if no input voltage is present, no up or down pulses are generated and the machine remains at zero, electrically at balance.

To demonstrate the up-pulse action, a +.009V is applied to the digital voltmeter. The polarity switch must be set to plus and the range switch to the 10V range. Application of this input voltage will cause the chopper to detect the unbalance, thereby creating a square-wave signal of proper polarity, which results in the "up" thyratron pulsing the first stepping switch — the least significant number in the right-hand window. This stepping switch will proceed to step up to the tenth position (0 equals first position) decreasing the unbalance at each step until the tenth position, the +.009V from the Kelvin-Varley divider, will balance the input voltage, causing the error signal to disappear. With the other decades still at zero, the instrument now illuminates +0.009 in the readout windows.

For a second trial run, +.099V is applied to the digital voltmeter. Again "up" pulses are generated to drive the first stepping switch. Observe that the switch will now step to the eleventh position, at which time the "up" pulses are transferred from the first stepping switch coil to the second stepping switch coil through the switch wiring. See Figure 12. The first switch is left in the nine position while the second one continues until a balance is reached at the tenth position, at which time the Kelvin-Varley divider arms reach a balance against the input signal. The readout now reads +0.099V. In a similar manner, increasing voltage inputs will cause the instrument to eventually reach the end of each stepping-switch position, and transfer to the next switch until a final reading of +9.999 volts is reached.

8. Stepping Switch Pulse Circuits — Down Pulses

"Down" pulses are routed through other decks of the stepping switches in a somewhat different manner. Starting with the digital voltmeter at +9.999 volts, assume that the input voltage has dropped to zero. With the Kelvin-Varley divider at +9.999 volts and the input at zero, a square wave of proper polarity is generated which results in the "down" thyratron pulsing the fourth stepping-switch

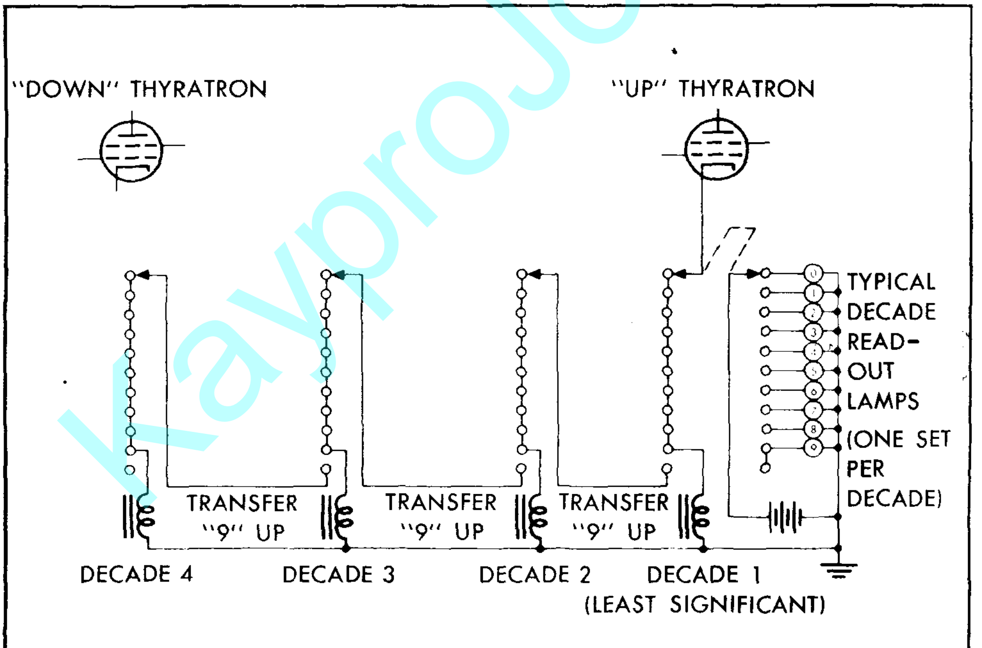

Figure 12. "UP" Pulse Switching Circuits.

coil. See Figure 13. A "down" pulse causes the switch to move one step, that is, to zero. Observe that the next "down" pulse is now transferred to the third switch coil which is at 9. One additional pulse results in the switch going to zero and again transferring the next pulse to the second coil. In this manner, four "down" pulses can reset the readout to all zeros.

In situations where the stepping switches are at settings other than transfer-point 9's, "down" pulses are routed through the least significant switch coil which is pulsed until a zero is reached. The "down" pulse, if it continues, is then transferred to the next most significant switch, which again repeats the sequence.

Under operating conditions, such as proceeding from .009 volts to .010 volts, the stepping switches go from 0.009V to 0.019V, which causes the "up" pulses to change to "down" pulses. By following the foregoing sequence, it can be seen that the least significant digit will be actuated so as to produce the correct number.

In this way, most inputs will cause a balance to be achieved by a combination of both "up" and "down" pulses. See Figure 14.

In a complete digital voltmeter, the wiring of the decade switches programs the action of the machine. Programming

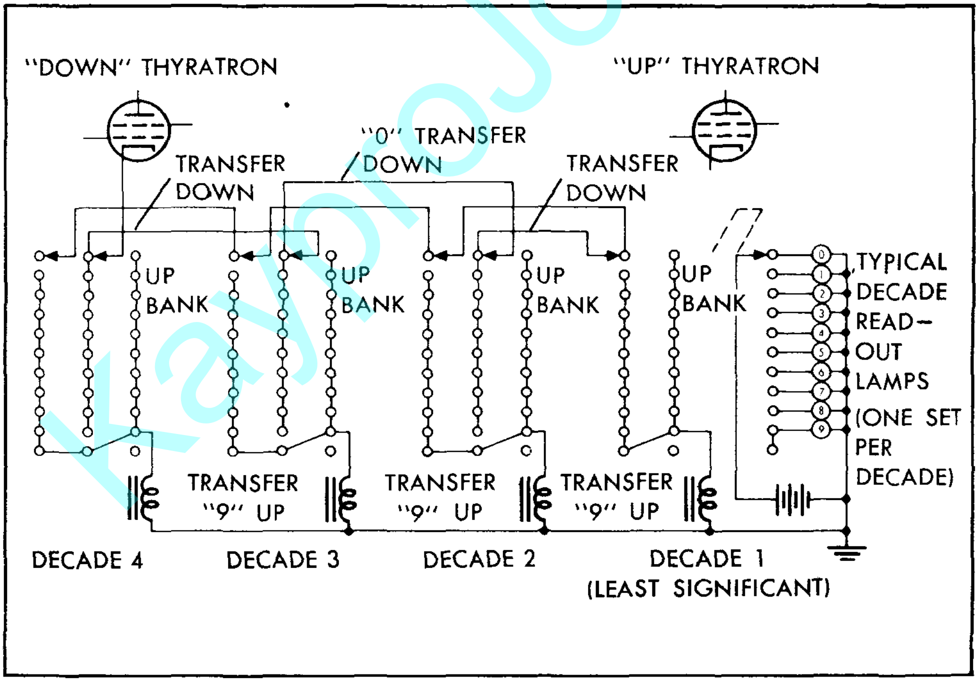

Figure 13. Down Pulse Switching Circuits.

circuitry which puts the correct voltage into the correct switch contact at any step of the process is referred to as logic. In most instruments a separately identifiable area, sometimes on its own printed circuit board, is called simply the logic.

Logic programming is a subject for separate study and, for this purpose, NLS instrument manuals will usually give the needed information and explain just how the logic circuits work in any particular instrument.

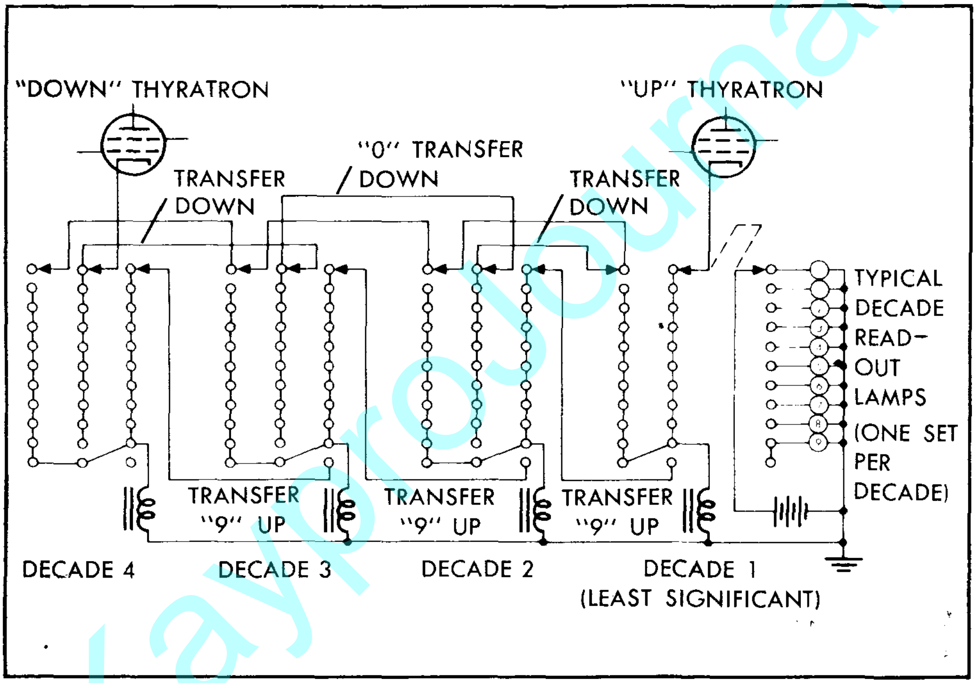

Figure 14. Pulse Switching Circuits.

The next chapter again returns to the basic potentiometer circuit and shows the way in which an entirely different instrument, the NLS Series 30, makes use of this principle.

Chapter III

NLS Series 30 Digital Voltmeters

The type V64A Digital Voltmeter described in the preceding chapter is typical of one approach to instrument design. This instrument is relatively uncomplicated and relies upon electron tubes and stepping switches to achieve a balance in a reasonable time.

However, the stepping switches used in this type of instrument must go through a whole series of maneuvers. This maneuvering action is produced by a series of overshoots as the instrument seeks an electrical null. As a result, the least significant numbers in the readout display may run to 9's and return back to zero several times before a final reading is reached. This hunting consumes a certain amount of time to complete a reading and causes disproportionate wear on the least significant stepping-switch decades.

To avoid this type of wear and to reduce balancing time, another design approach has been made. The NLS Series 30 instruments are completely transistorized, and while they also use stepping switches, mechanical wear has been reduced by not using the simple tracking logic of the V64 but instead using a scanning logic which is described in the following pages. This chapter discusses the specific circuits and concepts underlying the Series 30 instruments.

1. Basic Ideas

As indicated in the first chapter, digital voltmeters operate basically as self-balancing potentiometers. Recall that, as shown in Figure 1, at the beginning of Chapter I, an unknown voltage can be determined by adjusting the voltage divider until the reference voltage equals the unknown voltage. In this figure, the galvanometer indicates zero current flow when exact electrical balance exists. The voltmeter then indicates the voltage at balance. Note that when a zero current condition exists, there is no load on the voltage source being measured.

In order to produce an instrument which is capable of indicating voltage at the sub-millivolt level, some means of amplification is required. A technique frequently used, is to sample the unknown voltage with an electromechanical chopper which produces an easily amplified AC signal.

2. The Chopper

A chopper is basically a SPDT switch which is actuated by an electromagnetic coil assembly connected to a low-frequency AC source. As shown in Figure 15, the chopper arm is actuated by this source, contact is made with the unknown input signal voltage, and a capacitor is charged. On the next half-cycle, the arm swings to the other contact, discharging the capacitor into the primary of a transformer which feeds an amplifier. Because of the way in which the transformer primary is designed, a short pulse is generated during the discharge cycle. Note that the pulse polarity is related to the polarity of the unknown input voltage. Figure 16 illustrates a reversal of unknown input voltage polarity with the consequent reversal of output pulse direction. By using this chopper and AC amplifier technique, it is possible to amplify an unknown voltage at a sub-millivolt level until it

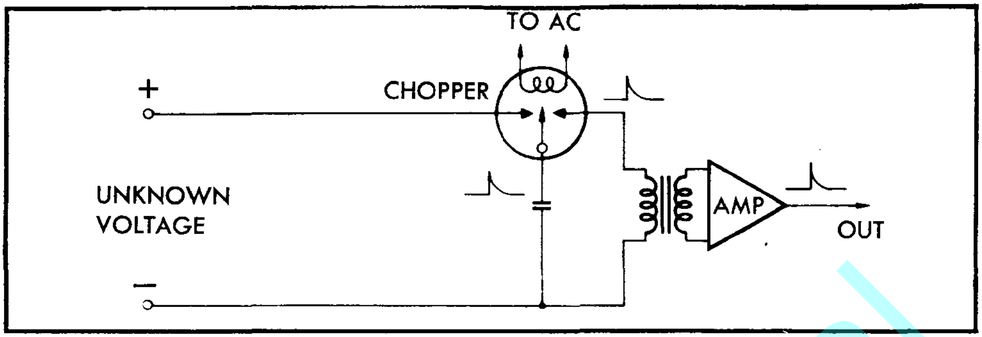

Figure 15. Positive Polarity Sensing.

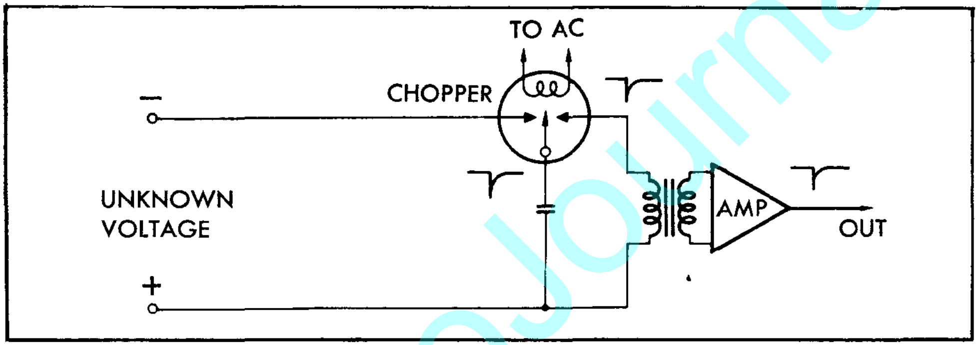

Figure 16. Negative Polarity Sensing.

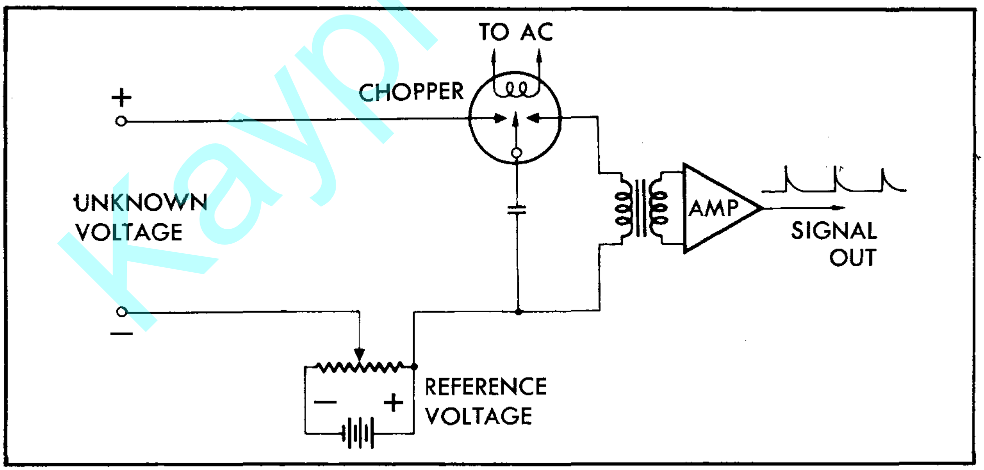

Figure 17. Voltage Nulling.

reaches a usable signal to actuate the digital voltmeter circuits.

The chopper circuit described here differs from the chopper circuit described in Chapter I. The earlier described chopper circuit is designed to produce square-wave forms which are preserved in the amplifier and later differentiated and used as trigger pulses. On the other hand, the Series 30 chopper here described generates these trigger pulses directly. These pulses are amplified and the pulse-wave forms are preserved in the amplification process until they are finally used as trigger pulses. With this type instrument there is no need to generate and amplify square waves.

Figure 17 illustrates how a known reference voltage can be applied to balance out an unknown input voltage. Adjusting the reference voltage until it matches the unknown voltage results in the capacitor "seeing" no potential difference as the chopper arm swings against the input contact. Since no voltage difference is present to charge the capacitor, no discharge occurs into the transformer primary, and no output is present from the amplifier. This null condition is analogous to what has been shown back in Figure 1, the basic potentiometer circuit at balance. The galvanometer has been replaced by an AC indicating device at the output of the amplifier, and the reference voltage can readily be measured with an accurate voltmeter.

3. An Elementary Digital Voltmeter

Figure 18 shows an elementary instrument based upon the ideas presented so far. A nine-volt reference source is divided into nine one-volt steps from zero to nine volts. Applying an unknown input voltage in one-volt steps from zero to nine volts will result in output pulses from the amplifier for every position of the voltage divider switch but one – the one that equals the unknown input. Ganging a second switch to the voltage divider switch, and operating a series of readout lamps to illuminate the correct number corresponding to the reference voltage, completes a manual one-digit instrument.

Figure 19 illustrates an automated version of the instrument shown in Figure 18. Here the amplifier is assumed to have sufficient output power to drive a stepping switch. Applying any input voltage, as in Figure 18, results in an amplified drive pulse which pulses the stepping switch until a switch point on the voltage divider is found that will balance against the unknown input. Again, a second switch section is positioned to illuminate the proper readout lamp indicating the voltage at balance.

4. A Practical Digital Voltmeter

A practical instrument must be able to measure a wide range of voltages, and, at the same time, protect the chopper from excessive voltage. This protection is achieved by placing a one-megohm resistor in series with the chopper and limiting the output of this resistor by adding a 12-volt zener diode to the circuit. See Figure 20. Figure 21 shows an input voltage divider used to extend the range of the instrument along with a chopper protection circuit.

In order for the reference voltage to balance against the unknown input voltage, the reference must be of the same polarity. To assure that the reference can reach a balance against an input signal of either polarity, a polarity-reversing switch is incorporated with the reference supply

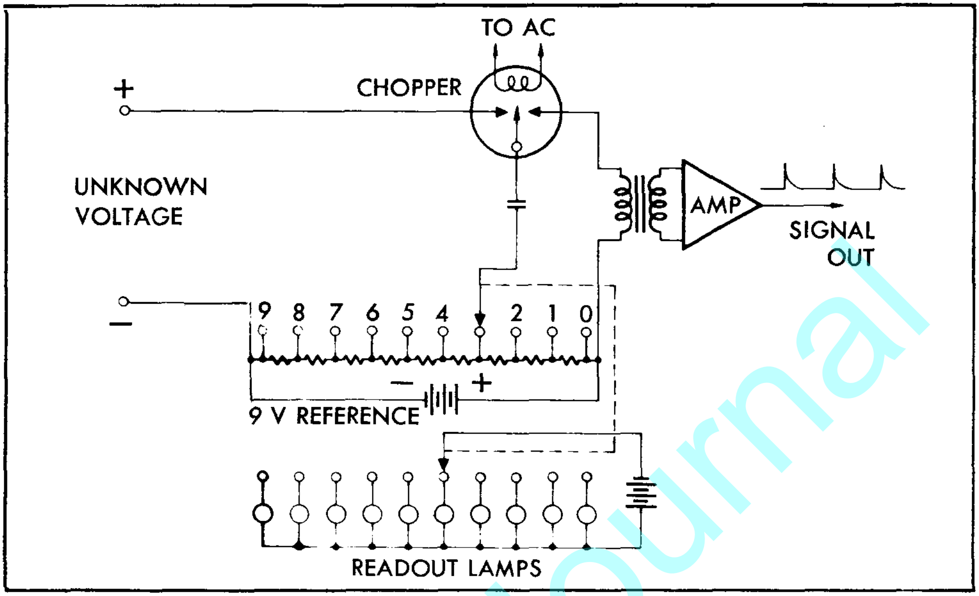

Figure 18. Elementary Manual Digital Voltmeter.

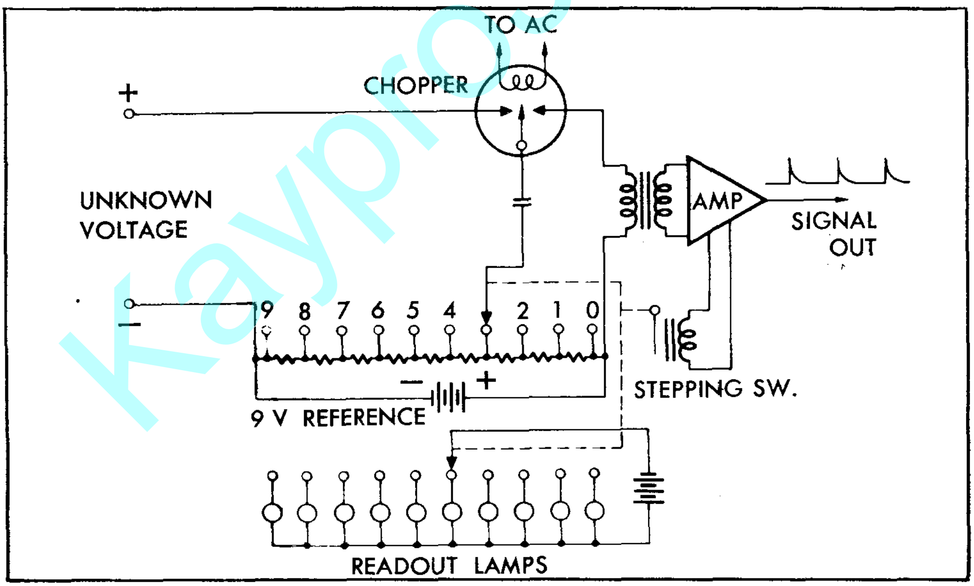

Figure 19. Elementary Digital Voltmeter.

voltage as shown in Figure 21. This figure illustrates the simplified input circuit of a NLS Series 30 Digital Voltmeter.

5. The Reference Supply

A digital voltmeter must contain an extremely stable voltage source as a reference supply if the instrument is to produce consistent readings over long periods of time. Figure 22 shows the reference supply used in the NLS 30 Series Instruments.

A 58-volt center-tapped transformer feeds a full-wave rectifier whose output is filtered by a 100 microfarad capacitor. The capacitor charging current is limited by a 5.6 ohm resistor. A 3.2K-ohm resistor and a 6-volt zener diode set the operating conditions for the base of a transistor constant-current source. Adjustment of the transistor collector current is made by a 200-ohm control in the emitter circuit. The collector current is passed through a bridge circuit, one arm of which is a matched pair of zener diodes. The purpose of the bridge is to reduce the effects of any possible current variations in the collector circuit as seen at the bridge output. A 17-ohm potentiometer adjusts the balance of the bridge, matching the zener impedance against its resistive arm. The zener diodes are of equal

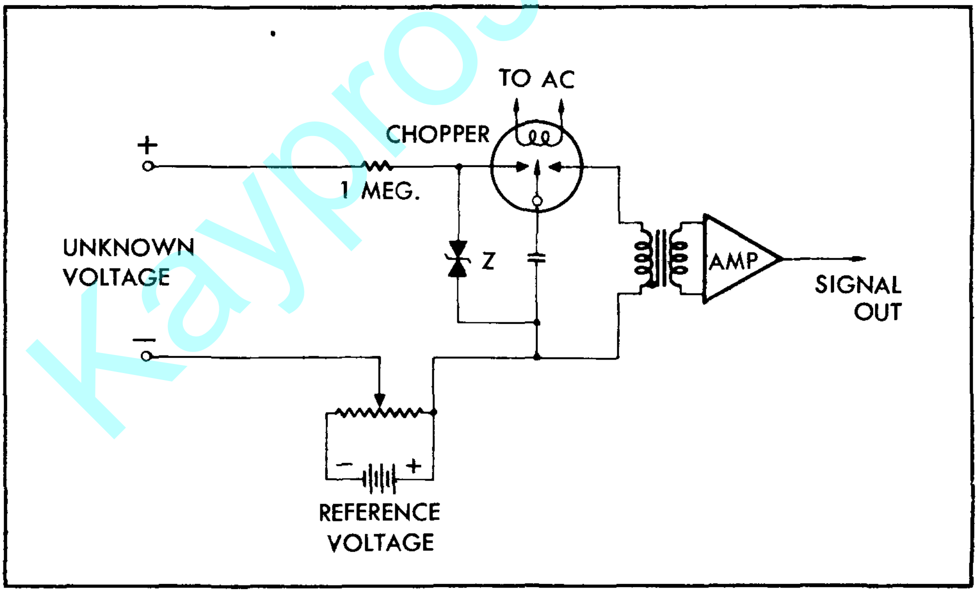

Figure 20. Zener Chopper Protection.

and opposite temperature coefficients, and are operated in a crystal type oven plug-in unit. The oven is operated from a separate DC supply not shown on the schematic, a supply which is thermostatically regulated.

This zener supply contains a polarity-reversing relay to reverse the output voltage. The output of the zener bridge is applied to a Kelvin-Varley type voltage divider through a series of dropping resistors and a calibrating variable resistance. These resistors are used to drop the zener supply from about 12.6V to 1V. The variable resistor makes the final calibration to exactly 10V.

6. The Kelvin-Varley Voltage Divider

To obtain the precise increments in voltage required of the voltage divider, a Kelvin-Varley type divider is used. The basic design of this divider has been modified so that the value of each decade resistor is the same, thus permitting each decade, along with its stepping switch, to be made into interchangeable plug-in units so as to simplify production, trouble shooting, and replacement.

As shown in Figure 22, each decade consists of eleven 5,000-ohm resistors. The output of any decade is selected by a pair of switch arms across two adjacent

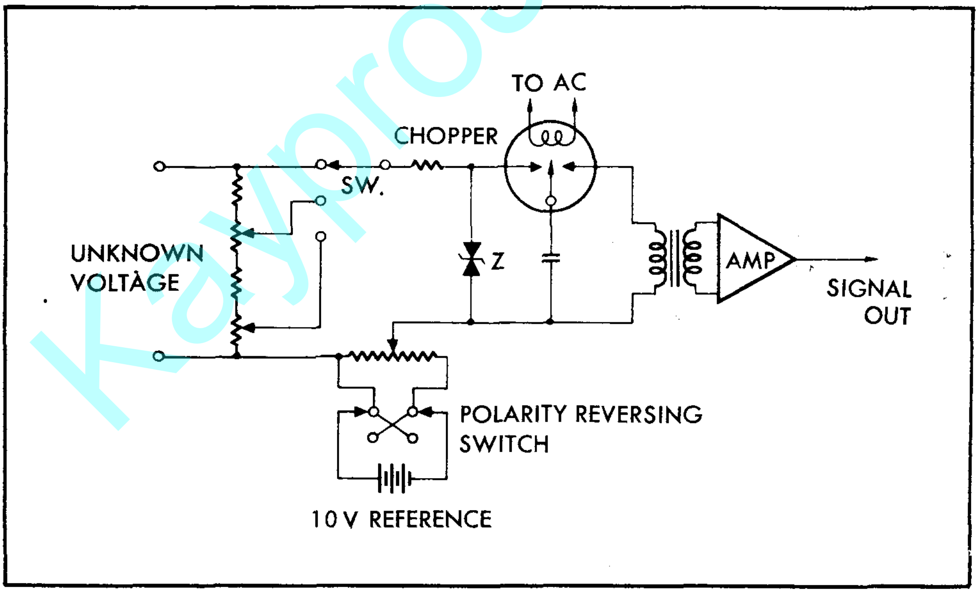

Figure 21. Range & Polarity Reversal.

5,000 ohm resistors. The switch arms feed the next decade of 55,000 ohms, which is shunted by a 12.5K ohm resistor, and shunted also by the following 55K-ohm decade, equaling 5,000 ohms. Under these conditions, the switch arms will select exactly one tenth of the voltage present across each decade.

By tracing the output of the reference voltage supply into the Kelvin-Varley divider, it can be seen that the voltage output of the most significant decade appears across a pair of switch arms. These arms bracket a one-volt region of the reference voltage. Once the desired voltage has been bracketed, it is passed on to the following decade which again brackets the voltage, but this time to within one tenth of a volt. The third decade is now able to select a desired voltage within one hundredth of a volt. In the fourth decade, a voltage can be selected in the millivolt region. Finally, in the fifth decade, a voltage can be selected in the 100 microvolt region. In Figure 23, the ten-volt reference has been bracketed down to produce a voltage of 5.4321 volts. Each decade, with its stepping switch, is built into a separate oil filled plug-in unit.

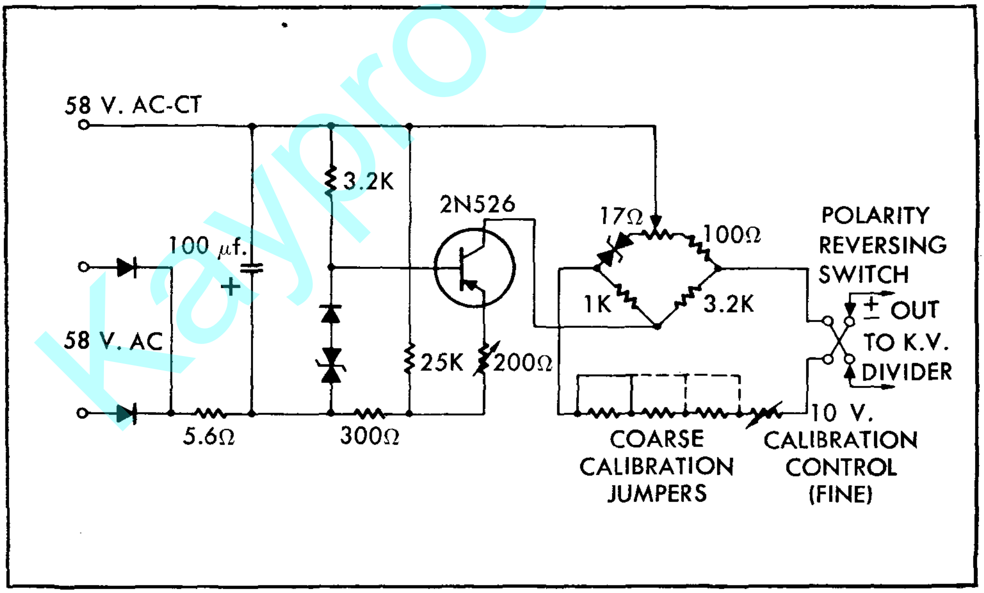

Figure 22. Zener Reference Supply.

7. A Manually Operated Digital Voltmeter

At this point, a review of the circuits so far described will help to clarify the operation of this type instrument. Figure 24 illustrates the meter up to its present stage of discussion. However, a new item, an 11-pole sequence switch, has been added. As a result, we now have a device which may be operated with manual controls to provide highly accurate digital voltmeter readings by observing the amplifier output with an oscilloscope and adjusting the switches for a nulled amplifier output.

The instrument can be best understood by applying an unknown signal voltage to the input terminals. First of all, in order to balance the reference voltage against the unknown input, the signal must be of the correct polarity. Figures 15 and 16 illustrate how signal polarity may be determined by observing the amplifier output. Similarly, grounding the reference voltage line and viewing the amplified output pulses will show signal polarity. The reference line is grounded by setting the sequence switch to the first position.

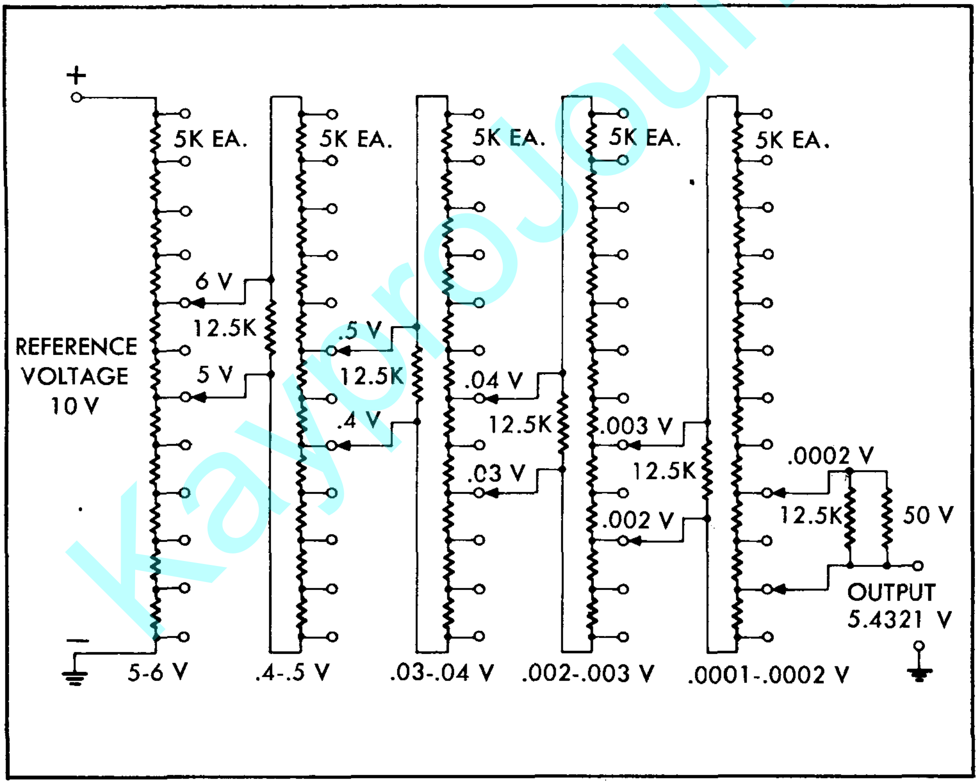

Figure 23. Kelvin-Varley Voltage Divider.

The reference polarity switch can now be set for proper polarity to null against the unknown input voltage. A second section of the polarity switch powers the proper plus or minus readout lamp to indicate polarity.

Secondly, in order to achieve a balance against the reference voltage, the input cannot be greater than the reference supply. This can be determined by applying the full 10-volt reference to the reference voltage line and noting if the amplifier pulse output is positive or negative. The 10-volt reference is applied by setting the sequence switch to the second position. A positive pulse indicates that the signal input is greater than the reference supply, and the range multiplier switch must be set to the next range (or the last range) when a negative pulse will appear at the amplifier output. The negative pulse indicates that the signal is less than the reference, and the reference may now be adjusted to null against the unknown input. A second section of the range multiplier switch is used to light automatically the proper decimal readout lamp.

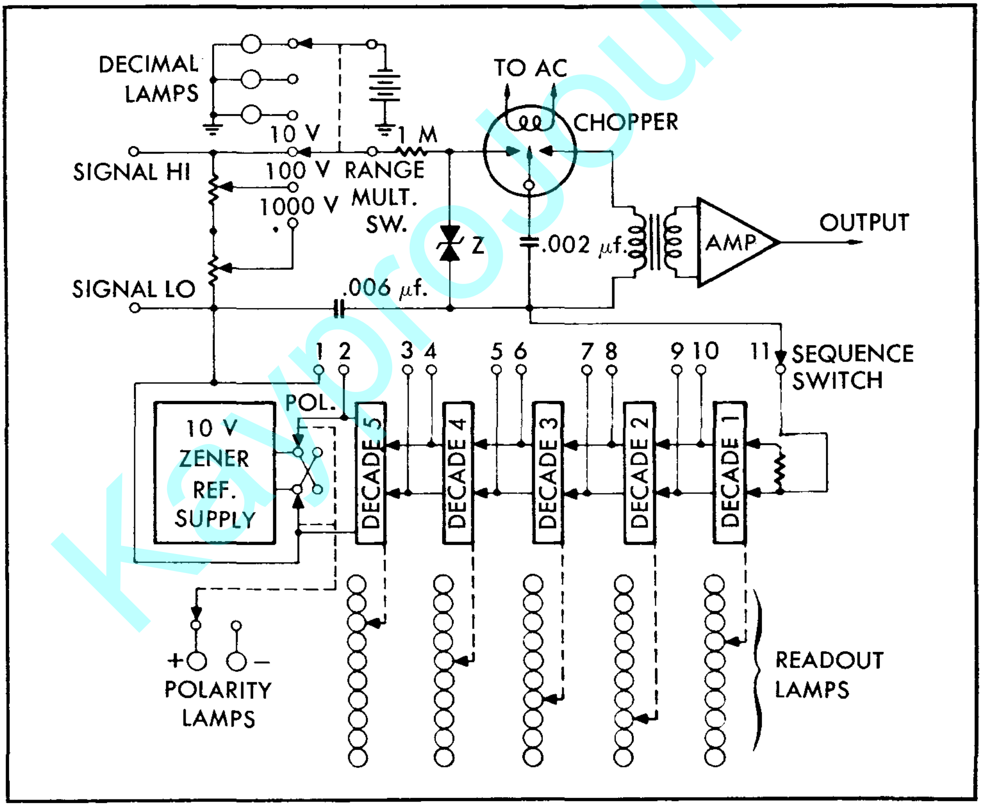

Figure 24. A Manually Operated Digital Voltmeter.

Thirdly, after polarity and range have been determined, it is possible to bracket the proper reference voltage, decade by decade in descending order, until a balance is reached. For example, assume that an input voltage of +5.4321 has been applied to the input terminals (Figure 24) and polarity and range have been set as earlier indicated. In order to determine that decade 5 (the most significant decade) output switch arms are bracketing the desired voltage area, 5 to 6 volts, the sequencing switch is now set to the third position, to the lower arm of the decade output. This position applies whatever voltage is present at that arm to the reference voltage line. The chopper then compares the input signal of +5.4321 volts to the voltage on the reference line. Should the reference line be at a higher voltage than the input, the amplifier output will produce negative pulses, indicating that the lower bracketing voltage is incorrect, that is, too high. The decade can then be switched (remember, stepping switches operate in one direction) until the lower bracket arm is less than the input signal, at which time the amplifier output pulses will be positive. It does not matter at this point what the specific voltage is, providing it is less than the signal. With the lower bracketing voltage found to be less than the signal, it remains to find the upper bracket. The sequence switch is now set to the fourth position which connects the top arm of the decade output to the reference voltage line. The amplifier output pulse polarity again indicates whether the input signal is higher or lower than the reference voltage line. Since the upper decade arm must be at a higher potential than the signal in order to bracket it, a negative pulse output from the amplifier is necessary. If the pulse is still positive, this means that both arms of the decade output are less than the signal and, to properly bracket, it will be necessary to advance the decade switch until a negative pulse results at the amplifier output. When the negative pulse appears, the decade arm is at a higher potential than the signal, so bracketing has occurred and the signal therefore must be between 5 and 6 volts. Another section of the decade switch is used to illuminate the proper readout lamp indicating the voltage at the lower bracket arm is 5 volts.

The bracketed one-volt area between 5 and 6 volts is shunted by the following Kelvin-Varley decade which can now bracket the voltage between 5 and 6 volts in .1 volt steps.

To bracket the proper .1 volt area in the fourth decade, the same procedure is used. The sequence switch is set to the fifth position, testing if the lower arm of the fourth decade output is less than the signal by observing amplifier pulse polarity, and adjusting the decade if necessary. With the lower arm set at less than the signal, the sequence switch is set to the sixth position, testing the upper arm bracketing voltage. Similarly, the output of the upper arm should be greater than the signal, producing a negative pulse output. If it is not, then the fourth decade is advanced until the bracket voltage is greater. Now this decade will bracket between .4 and .5 volts, passing on this .1 volt area to the third Kelvin-Varley decade.

This sequence is repeated for a total of 11 steps, when the final bracketed voltage is determined. With each decade properly set, the decade section connecting to the readout lamps will illuminate the proper numerals, indicating +5.4321.

If this procedure has been followed and understood, it can be seen that this sequence must be followed or an electrical balance cannot be reached with a minimum number of steps. At this point, a brief review of the bracketing procedure may be useful.

STEP	REASON
1. Check polarity and set if necessary.	Machine cannot balance if reference polarity is wrong.
2. Check range and set if necessary.	Machine cannot balance if input voltage is higher than available reference.
3. Check lower arm of 5th decade and adjust if necessary.	Must be equal to or less than input to be bracketed.
4. Check upper arm of 5th decade and adjust if necessary.	Must be greater than input to be bracketed.
5. Check lower arm of 4th decade and adjust if necessary.	Must be equal to or less than input to be bracketed.
6. Check upper arm of 4th decade and adjust if necessary.	Must be greater than input to be bracketed.
7. Check lower arm of 3rd decade and adjust if necessary.	Must be equal to or less than input to be bracketed.
8. Check upper arm of 3rd decade and adjust if necessary.	Must be greater than input to be bracketed.
9. Check lower arm of 2nd decade and adjust if necessary.	Must be equal to or less than input to be bracketed.
10. Check upper arm of 2nd decade and adjust if necessary.	Must be greater than input to be bracketed.
11. Check final decade arm.	Should be equal to or within 1 digit.

8. An Automated Digital Voltmeter

In order to convert this manual type instrument into an automated version, additional control circuitry is required. First, the sequence switch must be replaced with a stepping switch which will automatically go through exactly the sequence described. Second, some method of electronic control must be incorporated to stop and start the sequence switch during its travel through the 11 positions. This same electronic control must also integrate the action of each decade stepping switch as it seeks to bracket the correct reference voltage between sequence switch steps.

Figure 25 shows, in block diagram form, the material discussed up to this point in addition to circuits which are used to automate the instrument. The manual sequence switch is now a "transfer" stepping switch, and each decade switch, plus the transfer switch, is driven

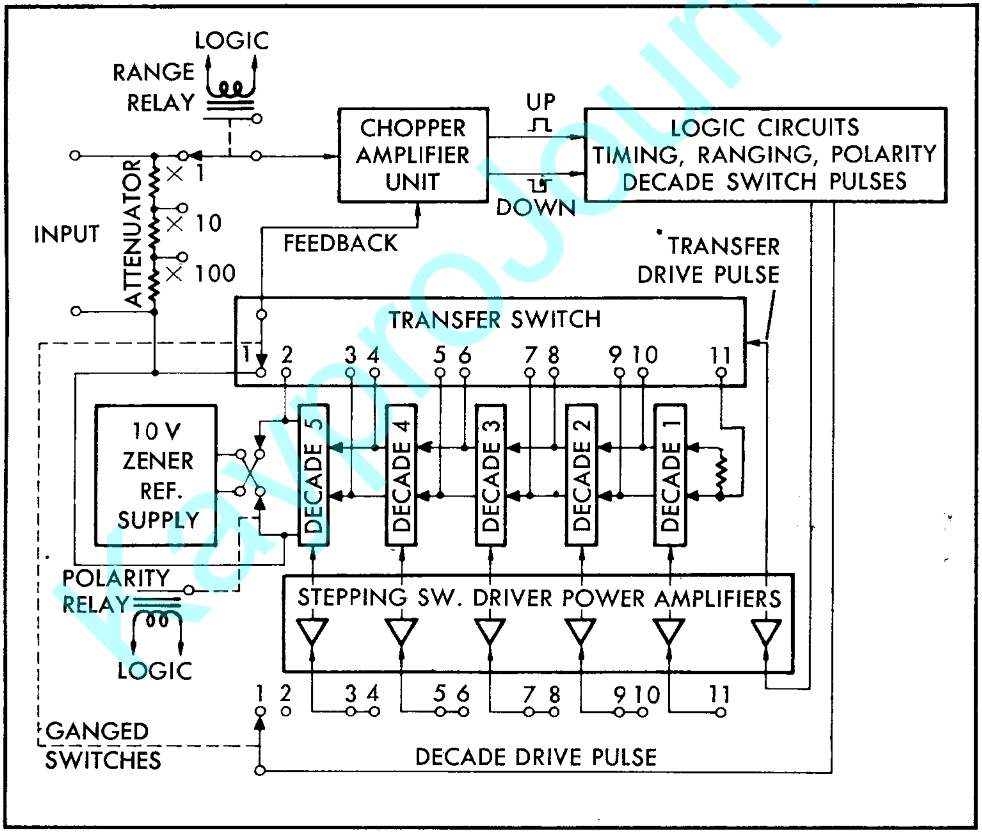

Figure 25. An Automated Digital Voltmeter.

by its own power amplifier. Each power amplifier receives its pulse signals from an electronic control area or "logic" circuit. The logic circuits, in turn, are actuated by the outputs from the basic amplifier along with its plus or minus polarity pulses.

To follow the operation of the automated instrument, assume that a voltage has been applied to the input terminals and that an imbalance exists between input and feedback (reference voltage). This results in output pulses from the amplifier, either up pulses (U) or down pulses (D). The logic circuits, responding to the presence of an error signal, set off the transfer switch which now must proceed through the same sequence earlier illustrated. Note that the first step grounds the feedback line, allowing the amplifier to produce a U or D pulse output, indicating the signal polarity to the logic circuits. The logic circuits, by way of a flip-flop, compare the amplifier pulse polarity with the polarity of the zener reference supply, and decide that the reference polarity is correct or incorrect. If correct, the flip-flop remains unchanged; if incorrect, it resets, tripping the polarity reversing relay. The transfer switch now moves to the second position connecting the feedback line to the full 10-volt reference supply. The presence of a U pulse from the amplifier indicates to the logic circuit that the input signal is larger than the 10-volt reference, activating a range switch relay flip-flop. When the amplifier produces a D pulse, the logic is satisfied that the signal is less than the reference, and the transfer switch moves on to the third position, now ready to test for proper bracketing voltages. Amplifier polarity again indicates to the logic circuits whether the lower bracketing arm is higher or lower than the signal voltage. If the voltage is higher, the decade switch continues to rotate until a lower voltage is reached. Then the transfer moves to the fourth step, testing the upper bracket of the decade for a higher-than-signal voltage. When this condition is satisfied, the transfer switch repeats this process for each decade switch until the eleventh step is reached. The instrument is now properly balanced; no U or D pulses are being generated, and the transfer switch remains at rest in the last position.

The Series 30 instruments have a front-panel control which sets the machine to operate automatically with any change in input voltage. The CONTINUOUS position allows the transfer switch to operate over and over while the SINGLE SCAN position permits the operator to initiate each individual transfer switch scan.

9. Recent Developments

A new design approach toward transfer switch techniques has led to the development of the Model V30B. This instrument eliminates the transfer switch and replaces it with eleven transistor-operated reed relays which duplicate the transfer switch closures to the feedback line. This change not only extends decade switch life, but permits additional switching flexibility. The transfer switch design inherently contains a built-in degree of inflexibility, and in order to balance, the instrument must go through the full sequence described in Section 7, if only to correct an error of 1 digit in the last decade.

The design approach of the V30B allows freedom to correct decades by individual reed relay closures, removing the need to proceed through the entire transfer switch sequence of 11 steps. In practice, this transfer switch is replaced by a transistorized package, the "programmer." This programmer contains reed relays, a unique counter circuit, and a matrix assembly. This programmer is fully described in the NLS V35B Manual. While essentially fulfilling the role of the transfer switch, the programmer has one great advantage; not only can it scan forward as the transfer switch does, but it can also scan backwards. Because of this ability, the instrument can correct errors in any decade by scanning backward as far as is necessary and then returning to the last step (11). A complete scan is required only when a polarity change has occurred.

In this handbook two basic types of digital voltmeters have been described, the Industrial Series instruments as typified by the NLS V64A, and the NLS Series 30 instruments. It can now be seen how a basic, low-cost digital voltmeter may be designed, one which possesses a high order of accuracy. This rugged instrument finds broad application in industry. Those users who require a more sophisticated instrument, one which uses a well-developed logic that minimizes stepping switch wear, frequently rely upon meters within the 30 Series.

In preparation are other handbooks of this series which describe instruments designed along other lines.

Glossary

In preparing this glossary it has been assumed that the reader is familiar with most conventional electronic terms. However, there are several terms which are fairly unique to the digital voltmeter industry, terms with which some readers may not be familiar. Not all of the entries listed appear in the text of this handbook, but it is hoped that the reader will benefit by their presence.

ACCURACY The limit which errors will not exceed when the instrument is used under prescribed conditions, or the difference between the indicated value and the true value of the quantity being measured under steady-state conditions.

BRACKET A voltage area between 2 contacts of a voltage divider which move in tandem. For example, a voltage divider may be tapped at 10 one-volt points from 0 to 9V. The voltage between any 2 tandem contacts may be considered as a bracketed area. See Figure 23 as an example of bracketing.

CALIBRATION In digital voltmeters, the adjustment of the reference supply voltage against a precision voltage source such as a bank of standard cells. The instrument is said to be calibrated when it reads the correct standard cell voltage.

CHOPPER An electromechanical device consisting of a vibrating member which makes alternate connection with 2 fixed contacts; in effect, a vibrating SPDT switch. Choppers are used to convert DC levels to AC-type signals. The frequency equals the chopper driving frequency, and the voltage output equals the potential difference between the 2 contacts.

COMMON MODE REJECTION The ability of a differential sensing device or amplifier to discriminate against a signal common to both differential input leads.

DECADE A precision voltage divider used in digital voltmeters. These are built into sections called decades, each decade corresponding to the numerical decade displayed by the readout.

GROUND In order to avoid unplanned circuit paths, ground circuits are isolated.

A. *Power* ground, usually the internal power-supply common circuit leads.
B. *Chassis* ground, a separate ground to power line ground to prevent shock hazards.
C. *Signal* ground. The signal return lead is generally isolated and fed to its own wiring to avoid having any common circuitry with spurious signals.

GROUND LOOP An unwanted signal entering the input lead. Typically, a common ground circuit carrying both signal ground and a second ground return will modulate one signal with another, causing an error in measurement. The lower the voltage measurement to be made, the more significant these errors become.

KELVIN-VARLEY VOLTAGE DIVIDER A type of voltage divider used in digital voltmeters to develop precise voltage increments. This type of divider exhibits a constant input impedance and can be built to use resistors of identical values.

OFFSET A condition in which a measurement made in one polarity does not numerically correspond to the same measurement made in the opposite polarity, or the inability of an instrument to indicate .0000 volts but to show some small plus or minus value. These effects are generally due to leakage paths in the instrument or external wiring, a hum modulation on the signal being measured, or a ground loop between the instrument and the circuitry being measured.

POTENTIOMETER A resistive device which allows the potential across the resistance element to be selected by means of a sliding adjustment or arm; or in special applications the adjustment is made in fixed steps.

RANGE ATTENUATOR A resistive divider used at the input of a digital voltmeter to reduce the input signal voltage to a level comparable to the internal reference supply.

RANGING A digital voltmeter has a basic range of voltage measurement equivalent to the internal reference standard. In order to read a voltage greater than this basic range, it is necessary to divide the input voltage down with either a manual range switch or with an automatic ranging circuit.

REFERENCE VOLTAGE In digital voltmeters, a highly accurate and stable voltage against which an unknown input voltage signal is compared. The digital voltmeter compares the input signal with the stable reference and displays the reference voltage at balance with the signal as if it were the input voltage.

SCAN The sequence of steps taken by a digital voltmeter within a program. At the last step, the machine is balanced, ending the sequence.

SENSITIVITY The ability of a digital voltmeter to respond to small voltage increments sufficiently to activate the balancing circuits and produce a new reading.

SIGNIFICANT DIGIT, LEAST The numeral displayed which has the least effect on the total reading displayed, *i.e.*, the right-hand digit.

SIGNIFICANT DIGIT, MOST The numeral displayed which has the most effect on the total reading displayed, *i.e.*, the left-hand digit.

STANDARD CELL A voltaic cell which maintains a specified voltage with greater accuracy than that obtainable from conventional carbon-zinc or mercury cells. Standard cells are used singly and in series to check the accuracy of precise voltage measuring instruments; in some cases, a standard cell is built into the instrument for convenience of adjustment. See CALIBRATION.

STEPPING SWITCH A rotary, electrically actuated switch which, by means of several banks (levels) of contact points arranged in a semi-circle, can provide many combinations of contacts. A moving contact (wiper) actuated by a solenoid drive mechanism, rotates within the circle of fixed contacts so as to make contact selections in a rotary sequence. These switches travel in one direction and, when given an electrical impulse, will cause the wiper to travel from one set of contacts to the next. Such switches are commonplace in telephone dialing circuits; more recently they have been used with digital voltmeters.

THYRATRON A gas-filled tube which can be triggered on by a control grid. The tube cannot be turned off by the grid but requires removal of plate voltage to shut off, after which the grid again resumes control. Thyratrons are capable of passing large currents under control of low grid voltages.

TRANSFER POINT When a digital voltmeter reading containing a 9 in the right-hand window changes to the next higher number, a transfer point has been passed. Examples: .009 to .010, .019 to .020, and .999 to 1.000. Conversely, 1.000 to .999, .010 to .009, etc.

ZENER DIODE A solid-state device which develops essentially a fixed potential across itself when operated within specified current conditions. This device is roughly equivalent to a voltage-regulating gas tube (VR-105 or OB2, etc.).