LABORATORY TYPE V.T.V.M.

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A vacuum-tube voltmeter of unusual stability and low-circuit loading, useful up to 200 mcs.

Fig. 1. V.T.V.M. with removable a.c. probe at right, ready to be connected directly to any R.F. circuit to be measured.

THE use of vacuum-tubes for measuring voltages present in high-impedance circuits as a means of minimizing the loading caused by application of any conventional measuring device to the circuit under investigation is old to the art—probably about as old as the high-vacuum, gas-free, triode itself. The basic concept is predicated upon the phenomenon of change in plate current of a vacuum tube resulting from change in grid voltage, and partakes of the amplification possibilities inherent in commercial triodes, pentodes, etc.

It is possible in a well-designed vacuum-tube voltmeter to reduce to practically insignificant proportions the apparent loading of a high impedance circuit, the voltage across, which is to be measured. This is a distinct and particular advantage of almost essential merit in investigation of radio frequency circuits. In radio receivers particularly, a series of cascaded parallel-resonant circuits are usually employed to derive amplified signal voltage from preceding vacuum tube amplifiers and to serve as a means of transferring such amplified voltage on to succeeding amplifier stages. In the design, and in the servicing, of such equipments the process is tremendously simplified if a means be available which permits the measurement of actual amplification per stage by the simple process of shifting meter terminals from the input of one amplifying stage to the output of such stage, and so on throughout the entire series of cascaded amplifying stages.

The need for such a measuring instrument has become increasingly acute over the past decade, during which the complexity and variety of radio frequency and electronic equipment circuits and functions has multiplied prodigiously. Today, while it is not impossible to service a complex radio receiver in the field without a vacuum-tube voltmeter, the process is so simplified if one be available that it seems safe to say that vacuum-tube voltmeters will be standard equipment for even the most unambitious serviceman in the postwar period. In a wartime period when competent design-engineering hours are of vital importance, the "vacuum-volts," as it seems convenient to call the V.T.V.M., is of priceless value in the speeding up the analysis of all sorts and kinds of high-impedance circuit developments.

Manufacturers have not been backward in offering "vacuum-volts" to the industry, some types having been on the market for substantially a decade, but these earlier models have left much to be desired. More recent instruments, offered under the name of "electronic voltmeters," are, in many cases, not true vacuum-tube voltmeters in that the minimization of circuit loading of the true vacuum-tube voltmeter has been frequently sacrificed to provide a multiplicity of voltage ranges of quite high, but nevertheless finite, impedance. For example, the electronic voltmeter might be thought of as a vacuum-tube voltmeter having a resistive range-multiplier shunted across the terminals of the circuit under measurement, with the actual "vacuum-volts" arranged so as to include more or less of such shunt resistance in its input circuit as a means of altering effective ranges of measurement. Such an instrument is, fundamentally, only an extension of the limiting ohmic resistance possibilities of the d.c. milliammeter, or d.c. microammeter, which constitutes the actual indicating device of the instrument. It is a means of increasing the meter resistance "seen" by the circuit under measurement well beyond that economically and mechanically possible to the meter itself. As such, it is a step in the right direction, but only a step. This is because the resistive input range-multiplier must be of some finite resistance which, in the case of radio-receiver, radio-frequency measurements, may still be sufficiently low to so load the circuit under measurement as to mask its true, unloaded performance. Such an arrangement will result in additional serious losses due to the lengths of connecting leads.

In the light of the foregoing, it may seem appropriate to regard as a true "vacuum volts" only an instrument presenting negligible resistive, capacitative and inductive loading to the circuit to be measured—an instrument presenting to the circuit to be measured substantially only the two terminals of the vacuum tube employed to translate the voltage appearing across a high impedance circuit into direct current which then actuates the actual visual indicating meter. The instrument illustrated and diagrammed herewith is such.

In order to accomplish a design satisfying the above requirement, a number of seemingly incompatible conditions must be reconciled, and numerous other factors taken into account. As a starter, the vacuum tube which must be employed as the a.c.-d.c. rectifier essential to translate a.c. volts into direct current to actuate the indicating meter, must have high inter-electrode resistance to keep circuit loading at a minimum. It must have low inter-electrode capacity to prevent both detuning and loading of the circuits to be measured. Automatically it must be a small receiving-type tube, since in addition to the above it must be so portable that its input terminals may be capable of application directly to the circuit under measurement to avoid the loading and losses of long connecting leads. Two inches of connection between circuit under measurement and the "vacuum volts" can be so serious as to destroy the validity of measurements made at radio frequencies previously considered high, but in conventional, widespread use today.

A vacuum tube of electrical and physical properties suitable for such application will be small in size, and hence limited in terms of voltages which may safely be applied to its electrodes. This means that it will be suitable, without an input range multiplier such as would deleteriously load the circuit to be measured, only for measurement of voltages within the maximum inter-electrode voltage rating stated to be limiting by its maker. Fortunately, in the present state of the art, this is not a serious limitation, since few, if any, circuit measurements which the freedom from loading which the vacuum tube voltmeter provides will require a range in excess of 100 volts. But a single range of 100 volts would render the "vacuum-volts" quite inflexible in terms of service applications, since its greatest usefulness will lie in accurate determination of voltages of much smaller magnitude.

Hence some sort of range-multiplier arrangement is essential to provide the variety of voltage ranges which will be needed in service if the instrument is to be truly useful. The range-multiplier will almost certainly be resistive in character, and it must be located, not across the input, but somewhere in the circuit of the instrument where it will be divorced from, and may not affect, the input characteristics thereof. The means of accomplishing this essential end—the end that differentiates the "vacuum-volts" from the simple "electronic voltmeter" falls nicely into place in the design problem when certain other requirements are satisfied.

The simplest "vacuum-volts" would be a triode between the grid and cathode of which would be applied the voltage to be measured, and which voltage would be indicated by the change in plate-current flow through a suitable meter and source of plate voltage. Such a system would be, and is, suitable for relatively coarse, qualitative measurements of potential, but is quite unsuitable for precise quantitative measurements. The reasons lie in the inherent instability of the vacuum tube itself due to the inescapable variations in applied plate and filament voltages when these be derived from commercial a.c. (mains) sources, which they must be if the final instrument is to be both versatile and portable.

If the actual measuring vacuum tube be a diode, the only variations which will seriously affect its stability will be filament voltage and its own internally generated contact-potential. Since plate voltage is not required, variations from this source may be neglected, while if the tube be of the popular, and almost universal, indirectly-heated cathode type, then thermal inertia coupled with judicious selection of heater voltage will swamp out quite effectively all significant variations due to heater voltage variation. Using a diode as the actual measuring vacuum tube, it becomes possible to follow it with a vacuum tube voltmeter of conformation such that the range-multiplier resistance network has no effect on input impedance for practical, and academic purposes.

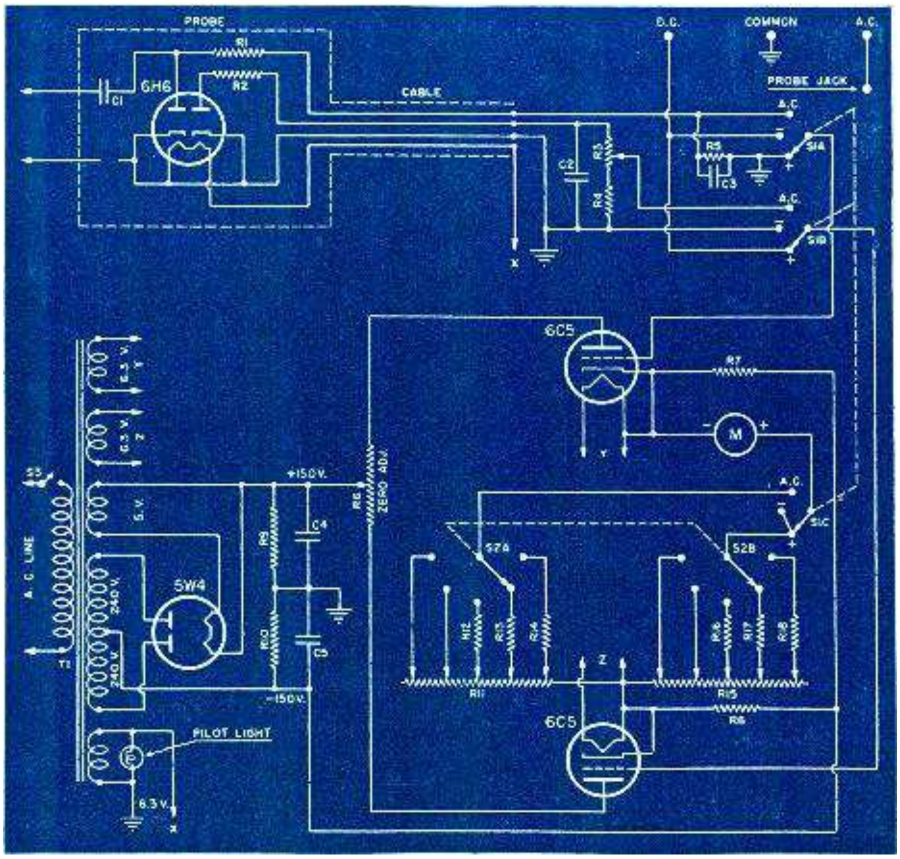

Fig. 2. Schematic diagram of the sensitive V.T.V.M.

C_1—.01 μfd. mica condenser
C_2, C_3—.1 μfd. 600 V. paper condenser
C_4, C_5—8 μfd. 450 V. elec. condenser
R_1—9 megohm ½w resistor
R_2—8 megohm ½w resistor
R_3—3 megohm volume control
R_4—3.5 megohm ½w resistor
R_5—5.4 megohm ½w resistor
R_6—3,000 ohm w.w. potentiometer
R_7, R_8—50,000 ohm ½w resistor
R_9, R_{10}—50,000 ohm 1w resistor
R_{11}, R_{15}—25,000 ohm adjustable w.w. resistor
R_{12}—15,000 ohm ½w resistor
R_{13}—70,000 ohm ½w resistor
R_{14}—220,000 ohm ½w resistor
R_{16}—40,000 ohm ½w resistor
R_{17}—135,000 ohm ½w resistor
R_{18}—440,000 ohm ½w resistor
T_1—Power transformer, 115 volts, 50/60 cycle, 3—6.3 volt secondaries, 1—5 volt secondary and 1—480 volt 40 ma. center tap secondary.
S_1—3P3P gang switch
S_2—2P5P gang switch
S_3—SPST toggle switch

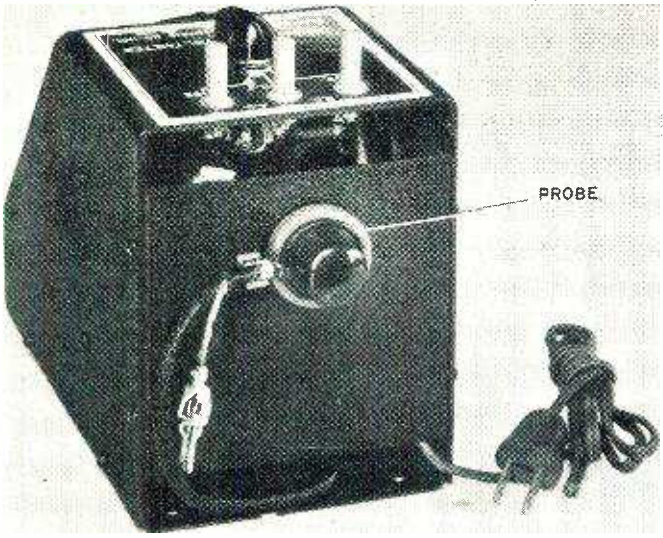

Fig. 3. Rear view showing a.c. probe inserted in its jack.

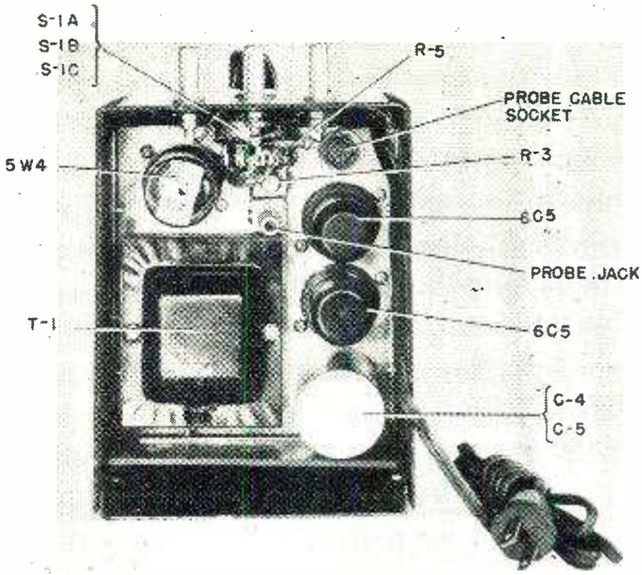

Fig. 4. Internal construction and parts layout of the V.T.V.M.

However, the problem of contact potential generated within the diode will still be present, and will operate disadvantageously upon the final effectiveness of the instrument. This contact-potential may be balanced out by the employment of two diodes, one for measurement of the voltage to be indicated, the second arranged to buck out the contact-potential generated within the measurement diode—somewhat in push-pull fashion, diagramatically. By means of a suitable, adjustable resistive load for the bucking diode, completely disassociated from the measuring diode, the contact-potentials of the two diodes may be made equal and opposite in sign.

The problem of insuring the minimally requisite order of stability for the following vacuum-tube voltmeter still remains. Fortunately the use of high orders of degenerative feedback in vacuum-tube amplifier circuits afford orders of stability obtainable simply and economically in no other way.

If two triodes be used, so arranged that their plate currents under resting conditions may be made identical, and if each be provided with a considerable percentage of inverse feed-back, then one triode may be used to cause a change in plate current proportional to applied grid voltage, while the second triode balances both the first triode, and the diode contact-potential through "seeing" the out-of-phase contact-potential developed in the second, or bucking, diode. The use of a high percentage of inverse feed-back operates to render the two triodes adequately independent of unavoidable fluctuations in heater and plate voltage.

The simplest means of obtaining the desired inverse feed-back is by means of a resistive load for each triode common to its plate and grid circuits in the common-cathode return circuit. If such load is common to both plate and grid circuits, then it will operate to subtract some significant proportion of total plate voltage from the plate circuit, and apply it as negative grid voltage. This presents an impossible condition, since in such case the triode grids would be biased so far negative that small changes in input voltage from the measuring diode would be unable to affect triode plate-current changes to actuate the meter. Since, in a practical instrument, the effective plate load of each triode is in its cathode return, common to plate and grid circuits, there seems at first little that can be done about it. Since the triodes are functioning as direct current amplifiers, the capacitive degenerative feed-back schemes possible to audio-frequency amplifiers are of no avail. The solution is to first provide the desired inverse feed-back needed to insure circuit stability against power supply voltage fluctuations by means of cathode resistors so large as to "cut-off" plate current in each triode, then offset the excessive negative grid bias resulting from this action by providing a direct current bucking voltage almost sufficient to do so, applied to the triode grid circuit only.

It now becomes possible to include the indicating meter in series with a range-determining resistive network connected between the two cathodes of the two triodes—completely divorced from the input circuits. By so doing an additional advantage is augmented, in that the current rise through the indicating instrument is limited in such manner that application of excessive voltage to the "vacuum-volts" as a whole will not ordinarily damage the meter—nor will a possible plate-to-grid or grid-to-cathode short circuit, resulting in a sharp rise in plate current in the event of tube failure, destroy the meter itself as it would were the meter connected directly in the plate circuit of one or both triodes.

Provision of the two diodes, with an insulating condenser to eliminate the d.c. component of any a.c. voltage to be measured in series with the input of the measuring diode, summarizes as an accessory unit to the "vacuum-volts" proper. It consists of the two triodes and associated circuit components. Degeneration makes them extraordinarily stable, and the arrangement described above of connecting the indicating meter and range-multiplier network between their cathodes now results in a d.c. "vacuum-volts" of minisculic circuit loading when the a.c. diode arrangement, most easily built as a detachable "probe," is removed from circuit and the d.c. voltage to be measured is applied to one triode grid only.

The d.c. "vacuum-volts" so provided will not only show higher input resistance, and hence less loading of circuits under measurement, than conventional magnetic or electronic voltmeters. but, like all d.c. meters, will possess polarity sense. To avoid the inconvenience of reversing connecting leads from the "vacuum-volts" to a circuit under measurement when the d.c. polarity therein may reverse, it is possible to arrange a selector switch to apply the potential to be measured to first one, then the other, of the two triode grids. This feature makes it possible to shift the meter to read d.c. potentials of opposite, or changing, polarity without reversal of external connections. The mere shift of a switch knob effects polarity selection and indication.

Faced with the need for sizable quantities of "vacuum-volts" immediately required in war work, and finding it impossible, despite high priority and precedence ratings, to procure satisfactory instruments upon the market, engineers were forced to take the earlier results of other units, modify them to suit the immediate needs and availabilities, and produce the instruments needed for their own rush work, rather

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than go out and buy them. This gave rise to significant mechanical and electrical simplifications in the instrument illustrated herewith, as well as the elimination of a multiplicity of inherently unstable resistors from the original design. Since the resultant instrument not only satisfies all of the premises propounded above, but constitutes that today hard-to-find entity, a true "vacuum-volts," and since it can be constructed and calibrated quite easily in other needful laboratories, some further description seems appropriate.

Approximately 5″ wide, 10″ deep and 6″ high, the "vacuum-volts" illustrated in Figs. 1, 3 and 4 is a most versatile instrument for the measurement of a.c. and d.c. voltages in the range of .1 to 100 volts. Since, as previously stated, a single range of 100 volts would not permit accurate determination of small fractions of such maximum such as are vitally needed in stage-gain measurements in r-f and a-f circuits, this maximum is broken up into five differing ranges such as to provide full-scale readability down to small fractions of 1 volt. This is accomplished by providing a switch to select resistor networks suitable for full-scale ranges of 1, 3, 10, 30 and 100 volts. The fact that these ranges are available for either a.c. or d.c. gives the instrument a total of ten ranges. The five d.c. ranges are all of equal and identical (linear) slope across the meter scale, the incremental progression for increasing applied a.c. voltage differing slightly therefrom. Two d.c. scales are provided, serving for the two essentially different ranges having factors of "1" and "3". Two similar meter scales are provided for a.c. ranges, with indication on the basis of r.m.s. values of a sine wave, or 71% of the peak value of a complex a.c. wave.

A total of four adjustments, plus on-off switch and pilot lamp, control all operations. One internal screw-driver adjustment on the chassis, seen in Fig. 4, permits balancing of the diode contact potentials in a.c. measurement. So stable is the instrument that once this adjustment is set, it may be forgotten until the characteristics of the diode change as a result of long usage. The knob to the left of the pilot lamp bezel is the triode "vacuum-volts" balance, connected between the triode plates and B+. It permits "zeroing" the meter before measurements are made. Again, so stable is the design that one setting of this zero-adjustment is usually sufficient for all ranges. Below the meter face is the range selector knob. On the top panel are three binding-post/jacks for a.c. or d.c. input connections, with, in front of them a 3-position switch knob to select between a.c. and either positive or negative d.c. input.

Of the three binding-posts, one is

literally a dummy, the second is for "ground" input on a.c. or d.c., and the third is for "hot" d.c. input. The "dummy" connects internally to the jack visible in Fig. 4 just above the power transformer along the vertical centerline. The probe containing the debased 6H6 dual-diode, a.c. input insulating condenser and the two diode load resistors may either be plugged into this chassis jack through an aperture in the rear of the instrument, as in Fig. 3, when low-frequency a.c. input connection may be made to the two instrument binding-posts, or it may be removed for r-f work and the probe plug and alligator clip connected directly to the circuit under measurement. This latter method eliminates connecting lead lengths which would destroy accuracy in r-f measurements by putting the measurement diode right at the points of circuit potential to be measured. The probe resonant frequency is above 300 megacycles, which allows accurate measurements to be made to 150 or 200 megacycles. The a.c. input resistance naturally decreases with frequency, ranging from above 1 megohn just below the broadcast band on down to a little less than 20,000 ohms at 100 megacycles. Well above 100,000 ohms input resistance for all frequencies below 10 megacycles, and of very low input, or shunt, capacitance, the instrument is universally useful.

Examination of the circuit diagram of Fig. 2 together with what has been previously set forth, will indicate operational functions of the various component parts. The power supply develops a total of approximately 300 volts of d.c., filtered by C4 and C5, and split into two 150-volt sections by R9 and R10. The upper section supplies plate voltage to the two 6C5 triodes, the 150-volt section below ground operating to almost offset the negative grid bias developed across the two feed-back resistors, R7 and R8.

Gang switch S1A, S1B and S1C select between a.c. and selected-polarity d.c. inputs. S2A and S2B select the range-multiplying resistors for a.c. and d.c. Since these resistors must be adjustable to initially set the calibration, by setting full-scale meter readings on the different ranges to agree with known input voltages, each multiplier is made up of a selected portion of one common 25,000-ohm adjustable, wire-wound resistor in series with ½ watt fixed resistors of appropriate values. While one 25,000 adjustable resistor would serve for setting both the five a.c. and five d.c. meter ranges, two are used, one for a.c. and one for d.c. This prevents the physical jamming and overlapping.

The parts list appended should enable any experienced serviceman to build such an instrument. A 0-1 milliammeter could be substituted for the 0-200 microammeter shown, with suitable changes in multiplier resistor values only, but would make 2 volts about the minimum possible range for full-scale meter deflection.

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