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[54] **METHOD OF AND APPARATUS FOR AUTOMATIC MEASUREMENT OF IMPEDANCE OR OTHER PARAMETERS WITH MICROPROCESSOR CALCULATION TECHNIQUES**

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[58] **Field of Search** .... 235/151.3, 151.31; 324/57 R, 57 N, 73 AT; 338/320; 340/347 AD; 323/121; 364/480, 482, 606, 570, 559, 551, 525, 602

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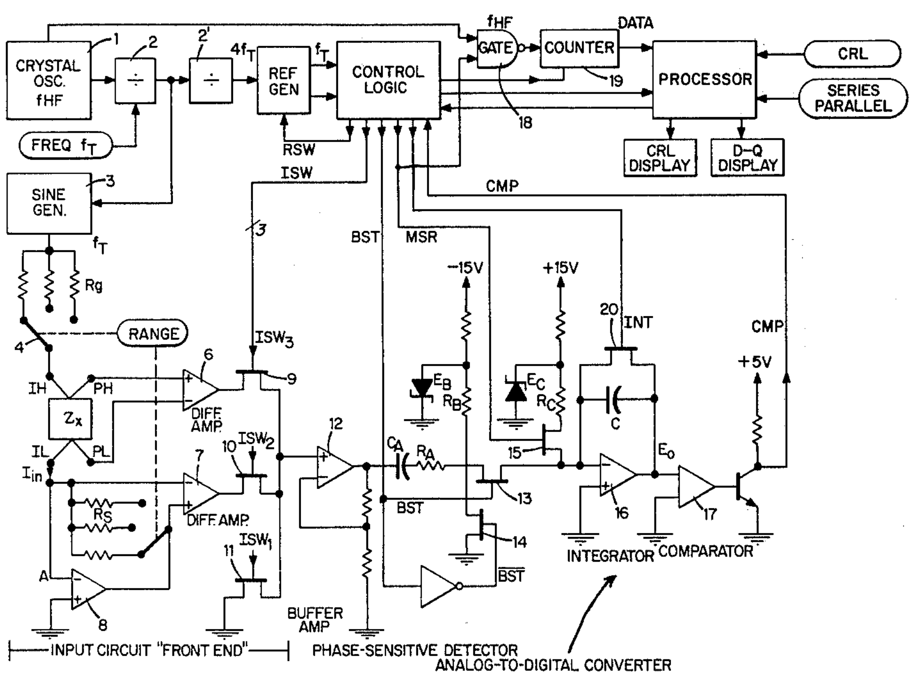
[57] **ABSTRACT**

This disclosure is concerned with a new technique for automatically measuring impedance (though the process is also applicable to other parameters and characteristics as well) wherein a series of voltages are sequentially presented to a common detector and analog-to-digital converter, the numerical values of which voltages are of themselves meaningless, but from which, with the aid of microprocessor calculating equipment, ratios may be calculated that indicate impedance (or other parameters).

33 Claims, 2 Drawing Figures



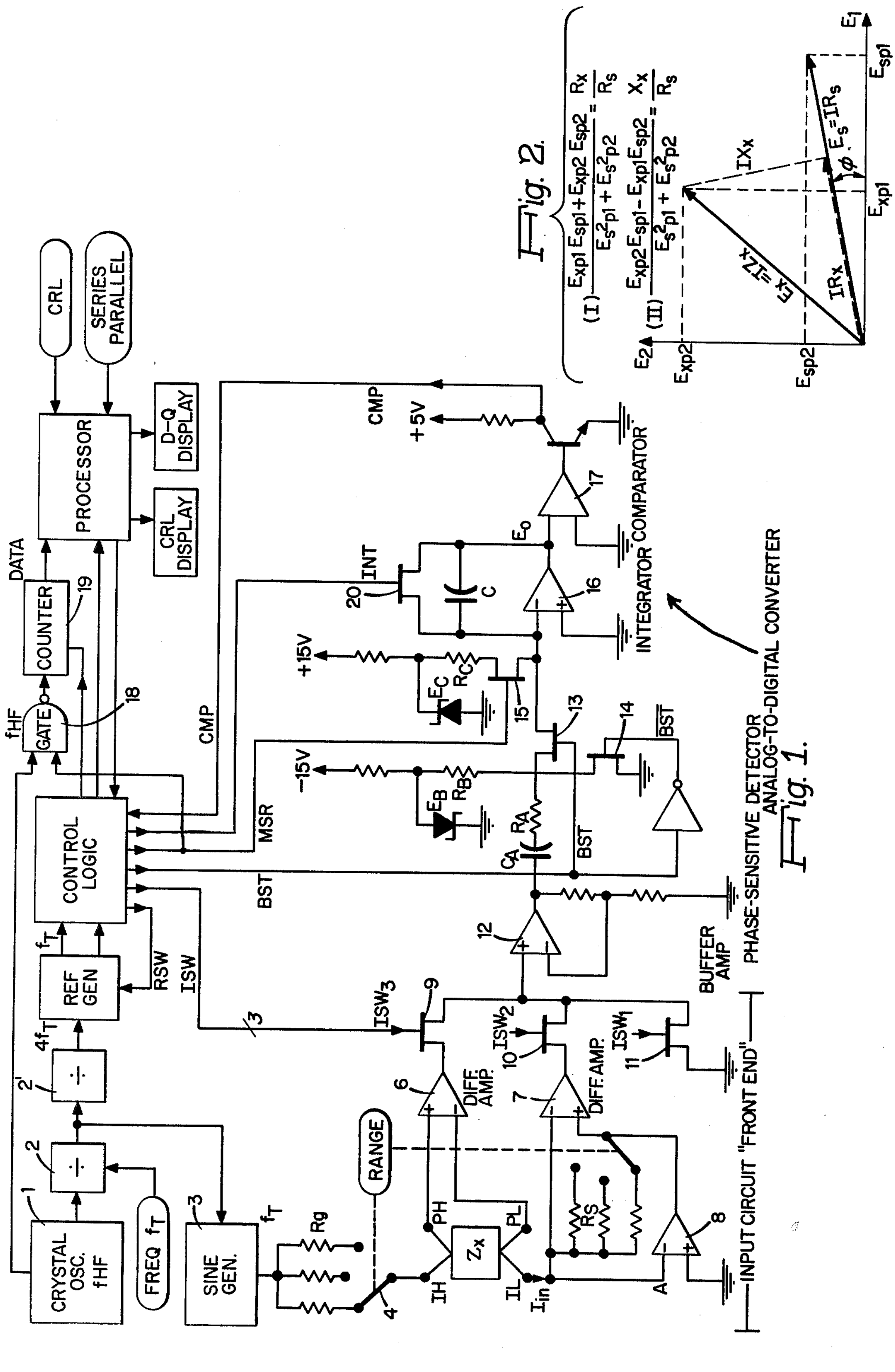


Fig. 1.

Fig. 2.

$$(I)\ \frac{E_{xp1}E_{sp1}+E_{xp2}E_{sp2}}{E_{sp1}^2+E_{sp2}^2}=\frac{R_x}{R_s}$$

$$(II)\ \frac{E_{xp2}E_{sp1}-E_{xp1}E_{sp2}}{E_{sp1}^2+E_{sp2}^2}=\frac{X_x}{R_s}$$

METHOD OF AND APPARATUS FOR AUTOMATIC MEASUREMENT OF IMPEDANCE OR OTHER PARAMETERS WITH MICROPROCESSOR CALCULATION TECHNIQUES

The present invention relates to methods of and apparatus for automatic measurement of impedance or other parameters and characteristics, being more particularly directed to the incorporation of microprocessor type calculating techniques to provide simplified measurement steps and instrumentation.

While the underlying philosophy or technique herein will be specifically described in connection with its illustrative application to automatic impedance measurement, it will be evident, as hereinafter more fully detailed, that the same is applicable also to other types of instrumentation wherein the same type of advantages may be sought.

The art is replete with bridge and related circuits evolved through the decades to enable the measurement of the electrical impedance of circuit elements. Because impedance, as defined by Ohm's Law ($Z=E/I$), is the result of a division, all impedance measuring instruments must in some manner effect a division. In general, impedance bridges embody the concept of using balancing network arms to obtain equal voltage ratios from which to determine the value of an unknown impedance element in one of the arms. As an illustration, a standard capacitor may be used as an arm to measure the current through an unknown capacitor in a voltage divider connection wherein the other bridge arms, serving as a calibrated divider, are adjusted to produce the same ratio by a successive balancing process producing different ratios until one is obtained that matches the capacitor ratio—in effect, a trial-and-error method of division. Of more recent years, such balancing has been effected with various degrees of automatic operation as described, for example, in my prior U.S. Pat. No. 2,872,639 and in Pat. No. 3,562,641. See, also, Fulks, R. G., "The Automatic Capacitance Bridge", GR Experimenter, April 1965. Such automatic balancing may employ digital-to-analog converters that produce certain voltage ratios which the detector indicates must be raised or lowered until the balance is obtained, again by this trial-and-error division principle. Inherent in such measurement systems, moreover, has been the requirement for long-term control and stability of circuit components and standards, and calibration requirements.

Other impedance measuring devices that do not use adjustable elements to obtain a balance are referred to as impedance meters. Some of these keep either the voltage across the unknown impedance constant or the current through it constant, so that the measured current or voltage is proportional to impedance or admittance, respectively, with only one quantity needing measurement. This, in effect, is division by a constant. Other meter-type instruments, on the other hand, measure voltage and current and obtain the ratio by analog division methods. (See, for example, Hall, H. P., "An AC-DC Ratiometer and Its Use in a CRL Meter", IEEE Transactions on Instrumentation and Measurement, December 1973, p. 387).

In accordance with the present invention, however, it has been found that through novel incorporation of certain calculating abilities of microprocessors in radically different network configurations, much simpler measurements may be made without trial-and-error balancing or bridges, void of the necessity for long-time voltage or current stability of certain meters, and void of the requirement for long-term component stability in both types of impedance instruments, and that revolutionize the automation of impedance measuring; it accordingly being an object of the invention to provide a new and improved method of and apparatus for automatic measurement of impedance, free of the long-standing disadvantages of prior art approaches above-discussed.

The use of such microprocessor or calculator incorporation is for quite a different purpose, moreover, than other relatively recent uses in instrumentation that are concerned, rather, with adding supplemental or additional functions or features to the instrument, enabled by the processor, such as readout techniques, more versatile control, interfacing with other equipment, or providing corrections for more accurate measurements. Reference may be made, for example, to an article entitled "Microprocessors Are Making the 'Impossible' Possible" By Jules H. Gilder, appearing in Electronic Design, No. 24, Nov. 22, 1975, commencing at p. 52, which describes such general micrprocessor usages; to a further article, "Microprocessor DVMs, With New Features, to Hit the Market Shortly", by Stanley Runyon, appearing in Electronic Design, 16, Aug. 2, 1975; and to Lee, R. C., "Microprocessor Implementation of a Measurement Instrument and Its Interface". An instrument-and-processor combination incorporating an impedance bridge to indicate parallel capacitance and D (dissipation factor) and a microprocessor to convert the data to series capacitance is described in the Boonton Electronics Corp. Mar. 4, 1975 specification bulletin Model 76A Automatic I MHz Bridge; this being the same function earlier attained with a separate automatic bridge and mini-computer. (See, for example, Operating Instructions for GR Type 2990-9174 "Automatic Capacitance-Testing System" Book 1, January 1970 of the assignee, herein, GenRad, Inc., formerly known as General Radio Company). While such incorporation of the microprocessor in the same housing as the bridge enables obtaining output data on the instrument in a more desirable form, it does not change the bridge circuit itself or its method of measurement operation. Use of the capabilities of a separate computer for increasing the accuracy of conventional bridge or meter methods for control and calculation purposes and the like are also described by Geldart, W. J., "Improved Impedance Measuring Accuracy with Computer-Operated Transmission Sets", IEEE Transactions on Instrumentation and Measurement, December 1975, p. 327; and in my articles "A Technique for Avoiding Correction Errors in Computerized Impedance Measuring Systems", and "Techniques Used in a Fast Computer-Controlled DC Bridge", appearing in the IEEE Transactions on Instrumentation and Measurement, November 1971, p. 249, and December 1974, p. 359, respectively; and to Julie, L., "A High-Accuracy Digital Instrument Design for DC Measurements", in the same IEEE Transactions of November, 1972, p. 323.

The before-mentioned use of the microprocessor for corrections, checks or calibrations is illustrated by an article by Tarczy-Hornoch et al, "Microprocessor-Controlled Self-Calibration and Diagnostics in a Digital Multimeter" (Systron-Donner Corporation) ELECTRO '76 Professional Program, May 11-14, 1976; and in "Impact of Microprocessors on Design of Analog

Instruments", by D. Abenaim of the assignee of this application, GenRad, Inc., presented at the said IEEE May, 1976 ELECTRO '76.

Other uses of computation in related circuits are found in U.S. Pat. Nos. 3,569,785 and 3,692,987, with the system of the former patent requiring multiple sample-and-hold phase-sensitive detectors for enabling impedance calculation.

Unlike these techniques, the present invention, in its application to impedance measurement, in summary, is concerned with the radical redesign of the impedance-measuring circuit itself, the substitution of a very different network that does not in any sense involve bridge-balancing techniques, that requires a pair of successive voltage measurements, of meaningless values in and of themselves, but that when applied to the microprocessor are used in a calculation to compute a meaningful quantity corresponding to the voltage-current ratio (previously effected by the successive approximation bridge adjustments) that represents the desired impedance value.

A further object of the invention, accordingly, is to provide a novel impedance measuring method and circuit apparatus that cooperates with microprocessor or similar calculator circuits in a new manner to effect impedance or related measurements.

Still another object is to provide simplified measuring steps and apparatus not only applicable to the automatic impedance measuring field but to determining other parameters, as well.

Other and further objects will be explained hereinafter and more fully delineated in the appended claims.

The invention will now be described with reference to the accompanying drawings,

FIG. **1** of which is a schematic circuit diagram illustrating a preferred embodiment illustratively shown applied to the exemplary automatic impedance-measuring application; and

FIG. **2** is a vector diagram of the measurement technique underlying the system of FIG. **1**.

Referring to FIG. **1**, the system basically involves a front end comprising a sinewave generator a.c. source **3**, controlled from a crystal oscillator **1** and frequency divider **2**, applied to a network comprising the unknown impedance-to-be-measured Z_x, connected in series with standard resistance R_s across the source **3**. Through respective differential amplifiers **6** and **7** and switches **9**, **10**, **11**, two successive measurements can be made; first, of the voltage E_x across Z_x, which may be stored, and then the voltage E_s across R_s. As hereinafter more fully explained, these voltages are applied to a common phase-sensitive detector and analog-to-digital converter, so-labelled, and thence applied to a microprocessor, labelled PROCESSOR, with its associated CONTROL LOGIC, to calculate the ratio E_x/E_s and thereby obtain a measurement of Z_x/R_s. Through the use of the microprocessor in this cooperative combination, division is effected in a simple manner with as many digits as desired; and the technique permits of the use of but a single detector. The detector, moreoever, and analog-to-digital converter, in the use required by this circuit and method, has the relaxed requirement of constant sensitivity only for the short measurement time; and, unlike prior art bridge and related circuits, has no long-term stability or drift requirements. The calibration factor involved in this measurement, moreover, cancels out in the division. Similarly, the input voltage or current I_{in}, unlike many measurement circuits, needs no long-term stability for measurements; it only needs short-term stability for measurement. The only parameter or quantity, indeed, that must be substantially constant over the long term or must have high precision and stability, in accordance with the invention, is the standard resistance R_s.

Still another improvement over prior bridge techniques underlying the invention is the resolution available over a wide range. For a conventional manual bridge with decade adjustment, for example, increased resolution is attained as full scale is approached; but at full scale, there is nothing further that can be done save changing a ratio arm to obtain a new range. This has to be done, furthermore, again and again over the entire range of the bridge, with resolution in a 10-to-1 range bridge varying from 10 to 1, and, on the lowest range, all the way to zero. With the novel E_x/E_s technique of FIG. **1**, on the other hand, there is no adjustable decade required and one does not run out of adjustment range. With the PROCESSOR, on the other hand, there is a floating decimal point, obviating the problem of running out of digits that forces range changes. The ratio of E_x to E_s, moreover, has a resolution error which is the sum of the errors of the two voltage measurements, producing successive symmetrical humped resolution curves as a function of unknown impedance range, as distinguished from reaching a top limit in prior art decade switching systems. This characteristic has the added feature of enabling a full range to be covered in a practical instrument (say from 0.1 to 10 M), with but three standard resistors R_s.

With regard to the analog-to-digital converter, a preferred type employs a dual-slope integrator **16**, as also discussed in my previously cited IEEE articles and in, for example, U.S. Pat. No. 3,074,057. The voltage output of the phase detector, later discussed, applies a current to capacitor C, shown above **16**, for a fixed time while switch **13** (an FET) is closed, causing C to integrate current in storing charge. When switch **13** is opened, switch **15** closes, and a current of opposite sign occurs in the discharge of C. The measurement of E_x and E_s, successively, at the input, results in a digital conversion that, upon ratio calculation in the PROCESSOR, causes all of the parameters including C, frequency, auxiliary voltage, etc. to cancel out in the equations such that no circuit values require the precision or stability of prior art bridges and the like; only short-time stability during the time required to make both measurements is required.

For a.c. measurements, involving complex numbers, the detector is of the before-mentioned phase-sensitive type to enable determination of the component of E_x that is in phase with the current I and the component that is in quadrature. Such a detector, as later delineated, provides IX_x and IR_x (where X_x and R_x are the reactive and resistive components of Z_x, respectively), from which C and L may be readily calculated, knowing the frequency. Thus, through the technique of the invention, unlike prior bridge techniques, no capacitance standard is used or needed, the reactance standard being the frequency. The only precision components, thus, are the three range resistors R_s and the crystal-controlled frequency. This type of detector **12**, etc. and analog-to-digital converter **16**, **17**, etc. in this setting provides added features of some rejection of harmonics and, with regular repeated measurements over some length of time, rejects completely the frequency that corresponds to this total time period.

Thus far, the use of the PROCESSOR with the circuit of FIG. 1 has been described in connection with the calculation of the basic division of otherwise meaningless voltage measurements into impedance measurements. This has the effect of reducing the amount of precision analog circuitry, enabling more reliable and less expensive instrumentation, as well. The microprocessor is also used herein to enable the making of corrections; not by adjusting the standard resistors as in prior art systems but by making measurements to determine the errors and inserting the corrections into memory.

It is now in order to describe in further detail the illustrated system of FIG. 1 and its underlying method of operation. The input circuit or front end is shown controlled by the previously mentioned state crystal oscillator source **1**; in this case, a high-frequency stable signal source. In actual circuits constructed and successfully operated, the oscillator **1** had a frequency f_{hf} of 25.1120 MHz. Frequency divider **2** feeds a reference signal f_T to generate a low distortion sinewave at **3**. While this may be done in any conventional well-known fashion, the sinewave generation may be effected, for example, by providing, say, 256×1020 Hz to the sinewave generator **3**, and employing therein an 8-bit counter that cycles through 256 addresses of a PROM (not shown), programmed so that it contains, in successive addresses, digital approximations to a sinewave at fixed phase angle increments, with the digital PROM output connected to a stepwise analog voltage by a D-to-A converter. Clearly, other sinewave generating techniques may also be used.

The sinewave signal from the generator **3** is applied to a set of current-limiting resistors R_g, selected by manual range switch labelled RANGE, which is ganged to control also the selection of the standard resistor R_s. Because the before-mentioned differential amplifiers **6** and **7** and the inverting amplifier **8**, connected across the standard resistors, all have very high input impedances, substantially all the current I_{in} flows through both the unknown impedance Z_x to be measured and the standard resistance R_s. The inverting amplifier **8** holds the junction A of Z_x and R_s at a virtual ground so that impedance between this point and ground would pass very little current, thus guarding the measurement from this source of error.

The two differential amplifiers **6** and **7** produce signals proportional to $I_{in}Z_x$ and $I_{in}R_s$. They use precision resistors in similar low-gain circuits so that their gains are stable and closely equal. Three switches **9**, **10**, and **11**, such as FET's or the like, select the input to a buffer amplifier **12** which can be the output of either differential amplifier or a ground connection for the zeroing measurement in this embodiment, though the switch **11** may be omitted with a 180 degree-type zeroing technique later described. For this embodiment, however, these switches are controlled by three ISW (input switch) signals from the control circuit, respectively labelled ISW_3, ISW_2 and ISW_1. The buffer amplifier **12** in turn applies the selected input to the before-mentioned ac phase-sensitive detector and analog-to-digital converter circuits. A capacitor C_A is added to block dc so that the offset voltages of amplifiers **6**, **7**, **8** and **12** do not affect the measurement. This allows the use of only one zeroing measurement to correct for offsets in the integrator amplifier **16** of the analog-to-digital converter and its comparator **17**. Adding the capacitor C_A requires that an additional switch **14** be used to keep this capacitor from charging as the gating switch **13** is off. If capacitor C_A is not included as for d.c. measurements, two zeroing measurements would have to be made to correct for offset voltages in the two differential amplifiers, and the input signal would have to be removed for these measurements.

A fixed dc current source, made up of E_B and R_B, insures that the current through the gating switch is always negative, no matter what the relative phase is between the reference and input signals, so that the integrator "up" slope is always up. The gating switch is driven by a burst of reference pulses (BST) generated from the crystal oscillator **1** by appropriate frequency dividers **2**, **2'** and a 90 degree reference generator (REF GEN), with the controller (CONTROL LOGIC) selecting the proper phase with the RSW signal, as is well known. The reference generator generates a pair of square waves (E_1 and E_2) that are 90 degrees apart from the signal $4f_T$, synchronous with E_x and E_s, but not phase related to them. In practice, this may be simply done, for example, with three flip-flops, enabling low nanosecond relative time difference operation. A value of D (i.e. dissipation factor R/X), as an illustration, of the order of 0.001 at 1 KHz represents only 160 nanoseconds, which is readily handled by the logic. As later more fully explained, from the two references E_1 and E_2 (FIG. **2**), the components of both E_x and E_s that are in phase with each of them can be obtained (E_{sp1}, for example, being the component of E_s in phase with E_1, etc.); and from these four quantities, the required ratios may be readily electronically calculated in the microprocessor as will be evident from the hereinafter discussed formulae I and II of FIG. **2**. This result, moreover, is independent of the angle ϕ between the references and E_s, such that not only may the generated sinusoidal test signal f_T have any phase, but the detector can also have any phase shift and any gain so long as it is constant for the short measurement time. An added advantage of this is the possible use of noise-reducing filtering in the detector without concern for phase shift.

A total of five measurements are made in accordance with this illustrative system, with integrator capacitor C shunted between each measurement with the switch **20** driven by the INT pulse.

The first measurement M_o is the zeroing measurement with the buffer amplifier **12** connected to ground. This measurement is a measure of the fixed current E_B/R_B plus the effects of any offset voltages or currents in the integrator **16** or comparator **17**. A burst of reference pulses is thus applied with either reference (reference **1** shown as used), and the integrator output voltage increases. Seventeen reference pulses have been used, for example, for the 1020-Hz signal (two for a 120-Hz signal) which makes this integration independent of 60-Hz (hum) pickup. After the burst is finished, the signal MSR (measure) opens switch **15** to discharge the capacitor C. When the output voltage is returned to zero, the comparator **17** produces a signal to stop the MSR pulse. The length of this MSR pulse is thus a measure of the zeroing signal and is measured by using MSR to gate the high-frequency signal f_{HF} at **18** into a counter **19**. The resulting data are fed to the processor as a count M_o.

The remaining four measurements use different combinations of inputs (ISW) and references (RSW) to obtain the various components of both input signals (IR_s and IZ_x) that are required to obtain the desired information. Since these measurements are all in error by the current E_B/R_B and the integrator and comparator offsets, the zeroing measurement M_o is subtracted from each of the other four measurements to get the four quantities used in the calculation of FIG. 2. This is an automatic, continual subtraction zeroing made for each voltage measurement as contrasted with an occasional. zeroing for calibration measurement. Indeed, in accordance with the invention, the subtraction zeroing measurement does far more than correct for errors; the impedance measurement is meaningless without it.

The before mentioned 180 degree-type zero measurement may alternatively be employed, removing the shorting switch **11**, and requiring a total of eight measurements. For this method, each of the four quantities (E_{xp1}, E_{xp2}, etc.) is determined by two measurements with reference signals opposite in phase (180 degrees apart). The difference between the two results is twice the desired quantity. The effects of offset voltages and the E_B/R_B current are cancelled by the subtraction. This has several advantages: (1) the two measurements are done more closely in time to reduce the effects of drift; (2) the measurements are averaged, reducing the effects of noise, and (3) non-linearity in the detector is cancelled to some degree.

As is evident from FIG. 2, the measurements are entirely different from the analog phase-shifting measurements of prior art bridges and the like and do not use E_x as a reference. To the contrary, 90 degree references E_1 and E_2 are used to enable two measurements of E_x and E_s, the voltages (IZ_x and IR_s) respectively across Z_x and R_s and constituting meaningless numbers per se insofar as impedance is concerned—one measurement with each reference. E_2 is plotted in FIG. 2 as the ordinate and E_1 as the abcissa, with the measurement vectors shown at E_x and E_s, the latter at phase angle ϕ. The projections of the vectors on the E_2 ordinate are E_{xp2} and E_{sp2}, and the corresponding projections on the E_1 axis are E_{xp1} and E_{sp1}. Equations (I) and (II) show how the ratios Rx/Rs and Xx/Rs may be caluclated from these measurement quantities in the microprocessor. These ratios must be multiplied by the value of R_S used for each range which is stored in the microprocessor. Only three range resistors are used because of the wide range it is possible to cover with each single resistor, as before explained.

When the calculated ratios are multiplied by R_S, the effective series values of resistance and reactance are thus presented. The measurement result, however, is sometimes required to be in terms of different parameters such as series capacitance and D or some other combination. If the frequency is known, and it is, and its value stored in the microprocessor memory, the microprocessor can, as is well known, calculate the result in any set of parameters desired. This can be done by first caluclating R_X and X_X and then converting them by appropriate formulae or by using other combinations of the variables in the equations of FIG. 2, and frequency. Thus, as indicated in FIG. 1, CRL or D-Q displays may be effected.

It should be noted, as previously explained, that the calibration factors of the dual-slope integrator and phase-sensitive detector may be cancelled by using only the one integrator and detector to make two measurements and dividing the results. More generally, the calibration factor of any linear measuring device may be cancelled when it is used to make two, or more, measurements and the result is calculated by taking ratios of these measurements. While previous measurements of resistance have been effected by taking two separate measurements with a single voltmeter or potentiometer circuit, and complex impedance can also be measured by taking three voltage (magnitude) measurements, these are a far cry from the complete technique of the invention enabling calculation automatically and in practical small, self-contained instruments embodying inexpensive microprocessors. It is the essence of the method herein described, moreover, that the data given to the calculator is not the result of an impedance measurement, but separate voltage measurements that are meaningless in themselves. Thus, one of the two measurements is not a calibration measurement. When the voltage across the resistance standard is measured, it is not measured to calibrate a resistance measuring instrument; but, rather, is a voltage measurement which is proportional to the current through the unknown, and requires the cooperative use of the calculator to measure impedance. By means of automatic switching, a single detector-converter receives a succession of input voltages, and the unknown impedance is automatically calculated from the results of these voltage measurements. The microprocessor used in this way, furthermore, enables all kinds of operation on the final data.

Clearly, the "front end" system illustrated in FIG. 1 may be modified for lower and higher frequencies; and the broad technique and philosophy underlying the invention may also be applied to direct-current systems for other uses wherein features of the invention are desired. Absent the front end, for example, a ratio meter is provided. If one input is connected to the input of a network and the other to the output, a transfer-function meter is achievable having advantageous features also provided by the invention, before discussed. If one input is a standard voltage, an a.c. or d.c. voltmeter may be constructed, providing average value for a.c. The technique also lends itself to phase-meter and even d.c. resistance meter application wherein the novel features underlying the broad method herein are sought. Further modifications for automatic electronic instrumentation embodying this novel philosophy and direction will also occur to those skilled in this art; and such are considered to fall within the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. A method of automatic instrument measurement of impedance, that comprises, measuring voltages across an unknown impedance element and a standard element connected to receive the same a.c. current to produce voltage signals the values of which are meaningless of themselves in terms of impedance values but that have theoretical ratio formulae relationship to the impedance values; converting the voltage signal values into corresponding digital quantities; employing a microprocessor to automatically electronically calculate the ratio of said quantities in accordance with said formulae; and indicating the calculated ratios to provide impedance measurement of said unknown element.

2. A method as claimed in claim **1** and in which said measuring is effected successively, with an initial measured voltage signal stored for presentation with a successive measured voltage signal to enable the said ratio calculation.

3. A method as claimed in claim **2** and in which the successive measuring of the voltages across the said elements is effected for 90 degree-displaced a.c. reference voltages, and said converting steps comprise the phase-detecting of the successively measured voltages

and analog-to-digital converting of the phase-detected voltages.

4. A method as claimed in claim **3** and in which zeroing measurements are effected to produce measured values representing fixed and offset voltages and currents associated with said phase-detecting and converting, and said measured values are subtracted from each of the voltage signal values prior to calculating said ratios.

5. A method as claimed in claim **3** and in which the fixed and offset voltages and currents associated with said phase-detecting and converting are removed by making two phase-sensitive measurements of each signal using detecting references that are opposite in phase, and subtracting the results.

6. A method as claimed in claim **1** and in which said measuring comprises determining the voltages E_{xp1} and E_{sp1} appearing across the unknown impedance element (X_x+R_x) and the standard element R_s, respectively, that are in phase with a reference signal E_1, and the voltages E_{xp2} and E_{sp2} appearing accross the unknown impedance element (X_x+R_x) and the standard element R_s, respectively, that are in phase with a 90 degree phase-displaced signal E_2, where X_x and R_x are the reactive and resistive components, respectively, of the unknown impedance, and the said ratio calculating is effected in accordance with the formulae:

$$\frac{E_{xp1} E_{sp1} + E_{xp2} E_{sp2}}{E^2{}_{sp1} + E^2{}_{sp2}} = \frac{R_x}{R_s}, \text{ and} \quad \text{(I)}$$

$$\frac{E_{xp12} E_{sp1} - E_{xp1} E_{sp2}}{E^2{}_{sp1} + E^2{}_{sp2}} = \frac{X_x}{R_s}. \quad \text{(II)}$$

7. A method as claimed in claim **6** and in which said calculating further includes the step of multiplying the ratios of equations (I) and (II) by R_s.

8. A method of automatic instrument measurement of impedance values, that comprises, generating an electric current in an instrument, producing, in response to that current, and measuring a plurality of voltages the voltage values of which of themselves do not measure desired impedance values, but that are theoretically related by formulae to such impedance values; converting the voltages into corresponding digital signals; employing a microprocessor to automatically electronically calculate said impedance values from said digital signals in accordance with said formulae; and indicating the calculated impedance values.

9. A method as claimed in claim **8** and in which said measuring step comprises effecting successive measured voltages and storing initial measurements to await successive measured voltages prior to said calculating step.

10. A method as claimed in claim **8** and in which said formulae involve ratios of said voltages.

11. A method of automatic instrument measurement of parameters, that comprises, measuring a plurality of voltages in a circuit the voltage values of which of themselves do not measure desired, meaningful quantities, but that are theoretically related by formulae to such quantities; converting the voltages into corresponding digital signals; employing a microprocessor to automatically electronically calculate said quantities from said digital signals in accordance with said formulae; and indicating the calculated quantities to provide measures of the desired parameters, said measuring comprising measuring 90 degrees phase-displaced components of voltages developed across an unknown impedance element and a standard element; and said calculating comprising obtaining ratios of digital signals corresponding to the measured voltages that determine the impedance components of said unknown element.

12. A method as claimed in claim **11** and in which, prior to said calculating, measurement is made of the effect of fixed and offset voltages associated with said converting, and the measurement value resulting from said measurement is substracted from each of the measured voltages.

13. A method of automatic instrument measurement of impedance values, that comprises, measuring a plurality of voltages in a circuit the voltage values of which of themselves do not measure desired impedance values, but that are theoretically related by formulae to such impedance values; converting the voltages into corresponding digital signals; employing a microprocessor to automatically electronically calculate said impedance values from said digital signals in accordance with said formulae; and indicating the calculated impedance values; said converting step comprising phase-detecting of the measured voltages and analog-to-digital converting of the phase-detected voltages.

14. A method of automatic instrument measurement of impedance values, that comprises, measuring a plurality of voltages in a circuit the voltage values of which of themselves do not measure desired impedance values, but that are theoretically related by formulae to such impedance values; converting the voltages into corresponding digital signals; employing a microprocessor to automatically electronically calculate said impedance values from said digital signals in accordance with said formulae; and indicating the calculated impedance values; said measuring step comprising effecting successive measurements and storing initial measured voltages to await successive measured voltages prior to said calculating step; said converting step comprising phase-detecting the successive measured voltages in a single circuit followed by analog-to-digital converting of the phase-detected voltages.

15. A method of measuring impedance and other electrical parameters without employing multiple-arm ratio bridge circuits requiring balancing variable impedance elements contained therein and null detection, which method comprises employing only a single arm containing an unknown impedance element and a standard element; applying reference sinewave signals 90 degrees phase-displaced across said elements; measuring the 90 degree phase-displaced voltages appearing across said elements, which voltages are meaningless in and of themselves but are related by theoretical ratio formulae to impedance; phase-detecting said voltages and converting the phase-detected voltages to digital signals; processing said digital signals in a microprocessor in accordance with said formulae and thereby electronically calculating ratios corresponding to impedance, in contradistinction to the technique of obtaining said ratios by the multiple bridge-arm variable impedance null-balancing detection.

16. A method as claimed in claim **15** and in which said measuring step comprises successively measuring the voltages appearing across said unknown impedance and standard elements in phase with each of the respective 90 degree phase-displaced reference signals, said phase-detecting and digital converting steps being performed upon the successively measured voltages.

17. A method of automatic instrument measurement of desired impedance values without requiring analog instrument measuring circuits wherein impedance values are measured and indicated by analog steps, which method comprises, providing an analog instrument measuring circuit with an input circuit restricted to those elements that are necessary to develop voltages at predetermined points thereof that, while meaningless in and of themselves, are related by theoretical formulae to impedance values that it is desired to measure; generating an electric current in the input circuit; producing said voltages in response to such current; converting the voltages to digital signals; and processing said digital signals in a microprocessor in accordance with said formulae and thereby electronically calculating the desired impedance values without the need of further analog circuits.

18. Apparatus for automatic instrument measurement of impedance having, in combination, an analog input circuit comprising an a.c. generator connected to a network containing an unknown impedance element and a standard element, and means for measuring the voltages produced across said elements by said generator, with the values of such voltages meaningless of themselves except as theoretically related by ratio formulae to impedance; means responsive to said voltages for converting the same into digital signals; microprocessor means provided with control logic and connected to said converting means for automatically electronically calculating impedance value ratios from said digital signals in accordance with said formulae; and means connected to said microprocessor means for indicating the calculated impedance value ratios to provide a measure of the impedance of said unknown element.

19. Apparatus as claimed in claim 18 and in which said converting means comprises phase-sensitive detector means connected to receive the measured voltages from the input circuit and connected to analog-to-digital converter means for producing digital signals corresponding to the phase-detected measured voltages.

20. Apparatus as claimed in claim 19 and in which means is provided for the zero-measuring of fixed and offset voltage and current values in said detector and converter means and for subtracting the zero measurement values from each of the said measured voltages.

21. Apparatus as claimed in claim 20 and in which the zero-measuring means comprises means within the analog-to-digital converter means for producing a signal measuring the zeroing signal; and there is further provided high-frequency signal means connected to counter means and gated in response to said zeroing signal to apply a count representative of the zeroing signal to the microprocessor means for subtraction from the digital signals corresponding to said measured voltages.

22. Apparatus as claimed in claim 21 and in which said a.c. generator, the 90 degree phase-displaced reference signals and said high-frequency signal are derived from a common stable source.

23. Apparatus as claimed in claim 19 and in which said a.c. generator comprises a source of 90 degrees phase-displaced reference signals, and said voltage measuring means includes means for measuring the 90 degree phase-displaced components of voltages developed across said unknown impedance and standard elements.

24. Apparatus as claimed in claim 23 and in which said voltage measuring means measures the said components of voltages developed across said unknown impedance and standard elements in successive measurements.

25. Apparatus as claimed in claim 24 and in which means is provided for storing first voltage measurement values to await successive voltage measurement values for subsequent calculation, and said phase-sensitive detector means is a single phase detector connected to receive all of the measured voltages from the input circuit.

26. Apparatus as claimed in claim 25 and in which said successive measurements are effected by alternatingly switching differential amplifier means connected across each of the unknown impedance and standard elements to said phase detector.

27. Apparatus as claimed in claim 26 and in which said phase detector comprises dual-slope integrator means.

28. Apparatus as claimed in claim 23 and in which the said formulae relating the measured voltage components E_{xp1} and E_{sp1} appearing across the unknown impedance element (X_x+R_x) and the standard element R_s, respectively, that are in phase with one of the reference signals E_1, and the voltage components E_{xp2} and E_{sp2} appearing across the unknown impedance element (X_x+R_x) and the standard element R_s, respectively, that are in phase with the 90 degree-displaced reference signal E_2 are:

$$\frac{E_{xp1}E_{sp1}+E_{xp2}E_{sp2}}{E^2_{sp1}+E^2_{sp2}}=\frac{R_x}{R_s}\text{, and} \qquad \text{(I)}$$

$$\frac{E_{xp2}E_{sp1}-E_{xp1}E_{sp2}}{E^2_{sp1}+E^2_{sp2}}=\frac{X_x}{R_s} \qquad \text{(II)}$$

where X_x and R_x are the reactive and resistive components, respectively, of the unknown impedance.

29. Apparatus as claimed in claim 28 and in which means is provided for multiplying each of the ratios of formulae (I) and (II) by R_s.

30. Apparatus as claimed in claim 29 and in which means is provided for displaying from said ratios at least one of CRL and D-Q.

31. Apparatus for automatic instrument measurement of impedance values having, in combination, input circuit means limited to those analog-operated circuit components necessary to develop voltages at predetermined points thereof that, while meaningless in and of themselves, are related by theoretical formulae to impedance values it is desired to measure; means for generating an electric current in the input circuit means; means for producing said voltages in response to that current; means for converting the voltages to digital signals; and microprocessing means connected to the converting means for processing said digital signals in accordance with said formulae and thereby electronically calculating the desired impedance values without the need of further analog circuits.

32. Apparatus as claimed in claim 31 and in which means is provided for presenting said voltages successively to said converting means, and means is provided for storing initial voltages while awaiting successive voltages prior to combining said voltages for the processing of the same.

33. Apparatus for automatic instrument measurement of parameters having, in combination, input circuit means limited to those analog-operated circuit compo-

nents necessary to develop voltages at predetermined points thereof that, while meaningless in and of themselves, are related by theoretical formulae to parameters it is desired to measure; means for converting the voltages to digital signals; and microprocessing means connected to the converting means for processing said digital signals in accordance with said formulae and thereby electronically calculating the desired parameters without the need of further analog circuits; said apparatus further having means for producing zeroing measurement values of fixed and offset voltages and currents, including those associated with said converting means; means for digitizing said zeroing measurement values; and means for subtracting the digitized zeroing measurement values from each of the digital signals corresponding to each of the said first-named voltages.

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