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The Design and Self-Calibration of Inductive Voltage Dividers for an Automated Impedance Scaling Bridge

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Abstract – The design and construction of inductive voltage dividers (IVDs) for use in impedance bridge applications in the 50 Hz to 1 MHz frequency range is described. Two dividers are described; one designed to operate from 50 Hz to 2 kHz and the other designed to operate from 2 kHz to 1 MHz. Preliminary comparison results of the new IVDs over the 100 Hz to 50 kHz frequency range are given. A new bridge to self-calibrate the IVDs is also described. The bridge is based on the straddling method and has been designed to characterize IVDs over the 50 Hz to 100 kHz frequency range.

Keywords – impedance, bridge, inductive voltage divider, transformer, straddling method

I. INTRODUCTION

At the National Institute of Standards and Technology (NIST) over the past several years, there has been an effort to improve the impedance measurement services of 2-terminal (2T), 3-terminal (3T) and 4-terminal pair (4TP) standard capacitors, resistors, and inductors, with respect to accuracy, range of impedance, and range of frequency. The effort has involved building new measurement systems to scale the primary realizations of the Farad, Ohm, and Henry using classical bridge techniques and, more recently, digital sampling and processing techniques, where appropriate.

The primary realization of the Farad at NIST is based on the calculable capacitor, a cross-capacitor whose capacitance (approximately 0.5 pF) can be found from a single length measurement, as described in [1]. The frequency dependent characteristics of 4TP resistance standards are based on calculable 100 Ω and 1000 Ω resistors [2]. At frequencies of 1000, 1592, and 15920 Hz, highly accurate manual bridges are then used to scale these values of capacitance and resistance to levels appropriate to support present capacitance and resistance measurement services [3,4]. While these bridges are highly accurate and relatively wideband, they allow only for the comparison of like impedances, i.e., capacitors may only be compared to other capacitors. The primary realization of the Henry at NIST is through a Maxwell-Wien bridge [5], and, more recently, a digital impedance comparison bridge [6], which relate known values of resistance and capacitance to inductance.

An automated, high-accuracy impedance scaling bridge to compare 2T, 3T, and 4TP standard capacitors, resistors, and inductors over the 50 Hz to 1 MHz frequency range is presently under development. This impedance scaling bridge is being developed to improve present impedance measurement services, as well as to extend these services to support recent improvements in the accuracy and stability of commercially available capacitance meters, LCR meters, and impedance standards. An initial design of the bridge has been constructed and tested with promising results. A detailed discussion of the bridge is given in [7]. The bridge was designed according to proven coaxial bridge techniques, as described in [3,8], but includes additional circuitry and measurement methods that allow for the comparison of unlike impedances, i.e., a capacitor can be directly compared to a resistor. A preliminary error analysis of the bridge components indicates that the major source of error is due to the ratio and phase error of the reference inductive voltage dividers (IVDs).

The purpose of this paper is to discuss the development of improved IVDs for this bridge and the development of a system to self-calibrate the IVDs.

II. PROPOSED APPROACH

In order to cover the impedance scaling bridge's frequency range of 50 Hz to 1 MHz, two types of IVDs were built; a low frequency IVD designed to operate from 50 Hz to 2 kHz, and a high frequency IVD designed to operate from 2 kHz to 1 MHz.

The low frequency, two-stage, single-decade IVD has been designed and constructed using the principles described in [9]. First, a 100 turn magnetizing winding of #18 wire is wound as a single layer on a toroidal, 1-mil supermalloy core of dimensions OD = 15 cm, ID = 11 cm, H = 3 cm. A second, identical core is laid on top of the first and then the two cores are enclosed in a toroidal mu-metal magnetic shield 2 mm thick, taking care not to form a shorted turn with the shield. A ratio winding consisting of ten turns of 10-conductor, twisted strand wire is then wound on the toroidal magnetic shield. To minimize winding impedances, #12 wire is used for each strand. The twisting of the ratio windings in this manner ensures tight magnetic coupling between the windings, and the shield minimizes magnetic leakage fields coupling between the magnetizing and ratio windings.

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Theoretically, a transformer constructed in this manner should have insignificant magnetic errors. However, any small capacitive currents that exist between the ratio windings, as well as between the windings and ground are the dominant sources of error. The errors are proportional to the winding impedances multiplied by the capacitive admittances. The capacitive admittances were minimized by minimizing the number of turns in the ratio winding, with a corresponding decrease in the amount of voltage the windings can support. Ratio errors were further reduced using a method to optimize the internal admittance load of the ratio windings, as described in [10]. The method involves making an exhaustive set of 3-terminal capacitance measurements between the separate ratio windings, with the shield and unused windings grounded. The measurements are then organized in a matrix, where equivalent capacitance calculations are performed for all taps. The equivalent capacitances are then used in a selection tree to find the optimal ordering of the windings, such that the mutual capacitances for all taps is nearly equal. The outcome is a suggested ordering for the windings and a set of values for external capacitors that have to be applied between each tap in order to optimize the internal admittance loads.

The high frequency, two-stage, single-decade IVD was designed and constructed using the principles described in [11,12]. As with the low frequency IVD, the two-stage design reduces the excitation current in the ratio winding, with a corresponding reduction in ratio errors due to any currents that may exist between the leakage admittances in that winding. First, a 40 turn magnetizing winding of #22 wire is wound as a single layer on a toroidal, 1-mil supermalloy core of dimensions OD = 6 cm, ID = 4 cm, H = 2 cm. The magnetizing winding is tapped at every other turn; these taps are then used to drive shields to guard the ratio windings. A second, identical core is laid on top of the first and then the two cores are enclosed in a toroidal mu-metal magnetic shield 2 mm thick, taking care not to form a shorted turn with the shield. A ratio winding consisting of ten lengths of RG 174/U coaxial cable is then wound four times around the shield, and the ends are connected in series to create a 40-turn winding with 11 taps at 0.0, 0.1,...,1.0. The outer conductor of each length of coaxial cable is driven at the mid-point of its length from the 0.05, 0.15,..., 0.95 taps of the magnetizing winding. The divider is then enclosed in a mu-metal box to shield against external fields. To further guard the IVD taps, each tap is connected to a triaxial connector using additional lengths of RG 174/U coaxial cable, where the outer conductor of each length of cable is connected to the inner shield of the triaxial connector and is driven by the 0.0, 0.1,..., 1.0 taps of an auxiliary, single-decade divider. In addition, the IVD's magnetic shield and outer mu-metal enclosure are driven from the 0.5 guard voltage tap of the auxiliary divider. The IVD is then encased in an aluminum enclosure with coaxial connections to all inputs and triaxial connections to all ratio winding taps. The objective of the above design is to minimize the effective inter-winding capacitances of the ratio windings, and thus minimize the capacitive current through them.

Several methods were considered to test the above IVDs. As an initial test, the IVDs were compared to one another over the 100 Hz to 50 kHz frequency range using an IVD comparison bridge, as described in [13]. Two comparisons were performed, the first with the low-frequency IVD ratio winding compensation capacitances disconnected and the second with them connected. The results of these comparisons are shown in Fig. 1. The results indicate that the low-frequency IVD compensation significantly improves performance, and that the relatively high resistance of the high-frequency IVD's ratio windings causes significant errors below 1 kHz. While this method is satisfactory for identifying relative behavior differences between the two devices, the lack of a reference IVD makes an absolute determination of the IVD errors impossible. In addition, since the IVDs were designed to operate over completely different frequency ranges, their dissimilar input impedance characteristics make a comparison between the two extremely difficult with this comparison bridge and valid only over a narrow frequency range.

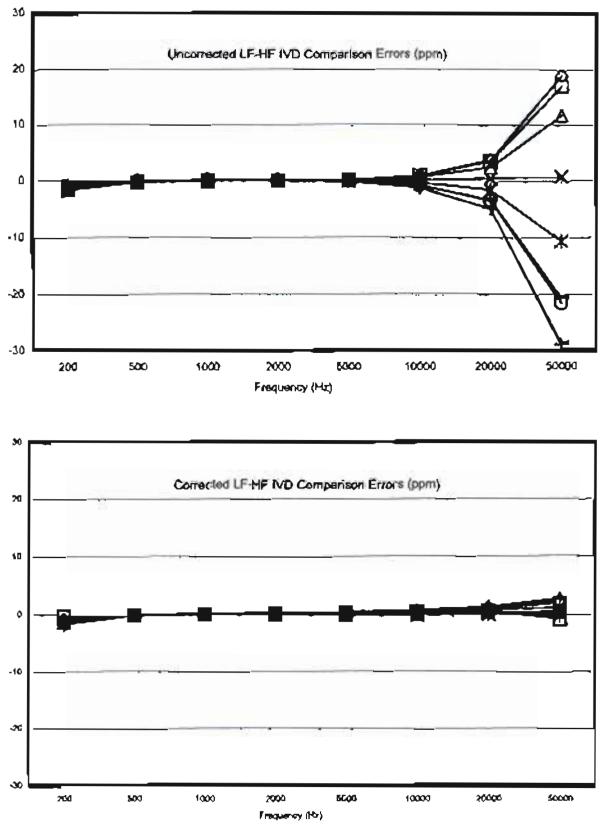

Fig. 1. Comparison of low-frequency IVD with high-frequency IVD illustrating compensation effectiveness

The other IVD characterization methods considered were those that allow for the self-calibration of an IVD. These include the straddling [14, 15], bootstrap [16], and permuting capacitors [17, 18] methods. Several factors were considered in order to decide which method to incorporate. Primary among these are overall system performance, complexity, and the ability to verify measurement errors. Due to the inherent symmetry and stability of the measurements involved, the straddling method was chosen to test IVDs in the 50 Hz to 100 kHz frequency range. The permuting capacitors method was chosen to test IVDs in the 100 kHz to 1 MHz frequency range and will be discussed in a future publication.

III. STEP-UP (STRADDLING) BRIDGE TO TEST IVDS

Fig. 2 shows the principal layout of the step-up (straddling) bridge that is used to calibrate inductive voltage dividers. An improved step-up method of IVD calibration was introduced by Grohmann of PTB [14] and was used in an international comparison in the late 1970's [12]. Hanke of PTB suggested some further improvements of the technique in the late 1980's using triaxial guarding techniques [15]. It should be noted that Fig. 2 is greatly simplified. The IVDs in the bridge are all two-stage devices, and the bridge contains additional circuitry to perform triaxial guarding, Wagner ground isolation, auxiliary signal injections, and phase-sensitive detection.

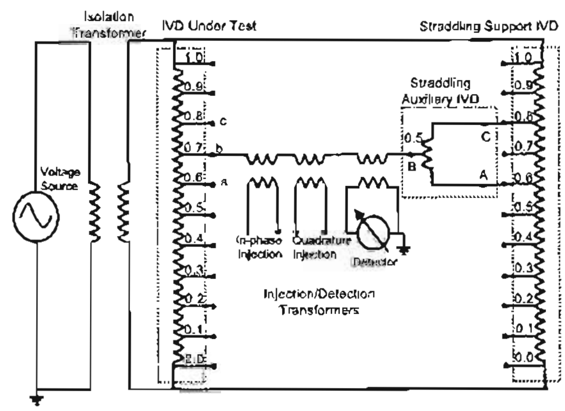

Fig. 2. Simplified diagram of the IVD self-calibration (straddling) bridge

In the straddling method, the IVD tap under test is straddled using a 1:-1 auxiliary divider (the 'Straddling Auxiliary IVD' of Fig. 2) connected across the taps above and below the tap under test. A single-decade drive IVD (the 'Straddling Support IVD' of Fig. 2) drives the auxiliary divider to the common-mode potential of the tap under test. With this method, the critical factor that determines accurate results is the common mode rejection of the auxiliary divider. The 1:-1 ratio errors of the auxiliary divider must remain consistent irrespective of the common mode level to which it is driven. This requirement is addressed by very careful design of guards. A detailed discussion of the design and construction of the auxiliary and support IVDs is given later in the paper.

The straddling method assumes that adjacent taps to the tap under the test can be accessed. All of the taps of the divider under the test are measured differentially against the auxiliary divider's center tap in a cyclical manner and the errors for each tap are then calculated from the cumulative set of difference measurements. The difference measurements are made using a triaxial, guarded, injection/detection transformer network, as shown in Fig. 3. A detailed discussion of the design and construction of this network is given later in the paper. As an example of the measurement method, Fig. 2 shows one of the difference measurements for the 0.7 ratio tap. There are three difference measurements necessary for each tap: Aa, Bb, and Cc. Another set of measurements is taken with the auxiliary divider input-output connections reversed. Then the procedure is repeated for the divider under test input–output connections reversed. There are a total of 108 difference measurements necessary to self-calibrate a one-decade divider. The in-phase and quadrature errors for each tap are then calculated from a decomposition of the cumulative set of difference measurements. For a detailed explanation of the mathematics involved, see [12].

A detailed discussion of the remaining key bridge components is given below.

IV. BRIDGE COMPONENTS

A. *Detection and Injection Transformer Networks*

There are two types of injection and detection networks used in the bridge, one with a triaxial design for the accurate measurement of differential signals, and one with a coaxial design for the injection of small compensating voltages and the detection of zero current conditions. These networks are designed in accordance with the techniques discussed in [15, 16, 19]. Simplified diagrams of the two networks are given in Figs. 3-4. The networks consist of three supermalloy cores, each with a primary winding of 100 turns wound in a single layer and enclosed in a copper shield (not shown in Fig. 3). The three cores are then enclosed in a cylindrical conducting shield, where they all share a common secondary winding made up of a single, shielded center conductor. The small air gap in the shield(s) around the secondary winding has the effect of significantly reducing the capacitance between the primary and secondary windings. The triaxial injection/detection network is used for the detection of the differential voltage between the IVD tap under test and the auxiliary divider tap, where the inner shield of the triaxial cable is driven to the same potential as the center conductor to prevent leakage currents in the dividers' ratio windings. The networks have been tested by driving each side of the center conductor with the same common-mode voltage and measuring the voltages induced in the primary windings. The common-mode rejection has been measured to exceed 1 part in 10^8 at 100 kHz.

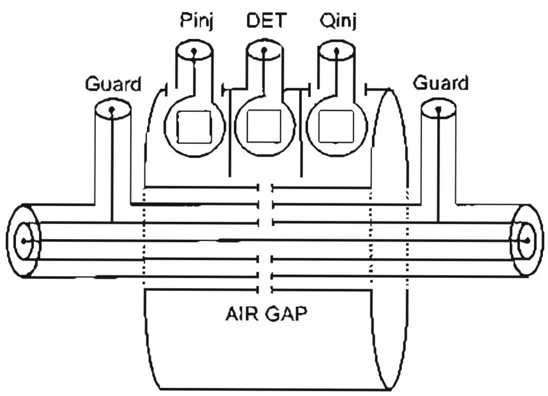

Fig. 3. Simplified diagram of the triaxial detection network

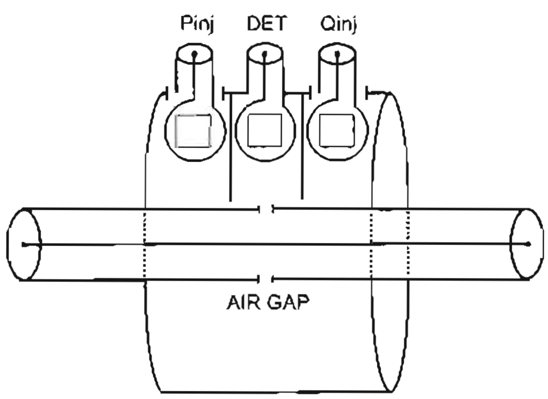

Fig. 4. Simplified diagram of the coaxial injection network

B. Isolation Transformer

The isolation transformer's primary winding consists of 45 turns of a 10-conductor twisted strand of #18 wire wound in a single layer on a high permeability toroidal core. The primary winding is enclosed in a toroidal magnetic and electrostatic shield. The low potential terminal of the primary is connected to this shield. A second, toroidal, electrostatic shield then encloses the first, with an isolating layer between them. The secondary winding consists of a similar 10-conductor twisted strand wound on top of the second electrostatic shield. The transformer is mounted in a mu-metal and brass enclosure and the second electrostatic shield is connected to it. Effective isolation between the primary and secondary windings is accomplished by driving the enclosure (the bridge ground) to a virtual ground (the primary winding ground) so that no capacitive currents exist between the windings. Since the secondary winding is wound with a twisted strand of ten wires, 11 output taps are provided, any one of which can be driven to a virtual ground, so that the divider under test can be measured in any grounded-tap configuration.

C. Straddling Support and Auxiliary IVDs

The straddling support IVD is a two-stage single-decade divider that serves to provide the various drive voltages for the the straddling auxiliary IVD, a two-stage, one-bit binary inductive voltage divider with a special shielding arrangement to maximize common-mode rejection. Both dividers are enclosed together in a shielded box that is driven at the bridge potential. The box has coaxial input connectors for the support IVD and triaxial output connectors driven by the auxiliary IVD. The support IVD's magnetizing winding consists of 45 turns of a 10-conductor twisted strand wound in a single layer on a high permeability toroidal core. A second, identical core is stacked upon the first, and a magnetic and electrostatic shield encloses both cores. The ratio winding consisting of 45 turns of a 10-conductor twisted strand is wound on top of the shield. The resulting 22 taps (11 magnetizing and 11 ratio) are then connected to a relay switch matrix that selects three adjacent magnetizing taps and two ratio taps corresponding to the highest and lowest of the selected magnetizing taps. The middle selected magnetizing tap is used to drive a mu-metal enclosure containing the auxiliary IVD. The remaining selected magnetizing and ratio taps are used to drive the magnetizing and ratio windings of the auxiliary IVD. The magnetizing winding of the auxiliary IVD consists of 128 turns wound on a high-permeability toroidal core. A second, identical core is then stacked upon the first, and a magnetic and electrostatic shield, isolated from the magnetizing windings, encloses both cores. The center-tapped ratio winding consists of 64 turns of 2-conductor twisted strand wire and is wound in a shoelace fashion on top of the shield. The shield is connected to the auxiliary transformer's mu-metal enclosure so that the ratio windings are sandwiched between them and consequently always see the same potential with respect to ground.

V. RESULTS

All straddling bridge components have been constructed and individually tested. The components are currently being packaged into a self-contained, automated unit. Self-calibration test results of the low frequency and high frequency IVDs will be given at the conference and in the final paper.

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