Journal of Scientific & Industrial Research
Vol. 65, June 2006, pp. 510-513

Design and development of high frequency standard inductors

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Received 05 April 2005; accepted 23 March 2006

A set of high frequency standard inductors (10 μH, 100 μH and 1000 μH) has been designed and developed. Such inductors, which are in the form of RC circuit having thin film resistors and high quality capacitor, show little variation at high frequencies. Also their terminals are provided with 4-TP (Four Terminal Pair) configuration, which is capable of minimizing residual impedances and stray field effects at high frequencies. These inductors serve as good inductance standards, which ensure high accuracy at high frequencies upto about 10 MHz. Such inductors would serve as echelon I level transfer standards at HF and are also quite suitable for calibration of 4-TP LCR meters/ impedance bridges.

Keywords: High frequency standard inductors, RC circuit, 4-TP configuration

IPC Code: H02M1/15

Introduction

For an inductor to serve as standard at high frequencies (HFs), its inductance value should change very little with increase of frequency. However, inductor wound in usual form of a coil has unwanted parasitic impedances, such as coil resistance and distributed capacitance; which significantly influence inductance value at high frequencies. Therefore, coil type inductance standards usable in HF region (>100 kHz) are substantially unavailable[1,2]. To overcome this problem, standard inductors have been designed in the form of RC network (Fig. 1a). T-network of this figure can be changed to equivalent ∏ network (Fig. 1b), such that branch impedance Z_B is given by[3]:

$$Z_B = R_1 + R_2 + jw\, R_1 R_2 C_3 \qquad (1)$$

where R_1 and R_2 are thin film resistors and C_3 is a high quality capacitor.

The inductance component (L_B) of impedance Z_B is given by:

$$L = R_1 R_2 C_3 \qquad \ldots (2)$$

This relation shows that by employing appropriate values of resistors (R_1 & R_2) and capacitor (C_3) in the form of RC network (Fig. 1a), inductors of various values can be obtained. However, the terminals of such inductors are fitted with four coaxial connectors of BNC type, so as to get four terminal pair (4-TP) configuration with two current and two potential terminals. Such a 4-TP arrangement has distinct advantages and can be looked upon as four terminal arrangement with a built-in shield around each terminal. The 4-TP approach provides improvement of precision for low impedance devices by eliminating uncertainties caused by lead impedance/ contact impedance, while the shielding around each terminal eliminates error due to shunt admittance. Another distinctive feature of 4-TP configuration is that the outer shield conductor works as the return path so that the same current flows through both the center conductors and outer shield conductors, but in opposite direction. Thus net current between the terminal pairs is suppressed. This reduces errors that otherwise might be produced by stray fields. As such the 4-TP inductors can serve as good inductance standards[4] ensuring high accuracy at high frequencies upto about 10 MHz.

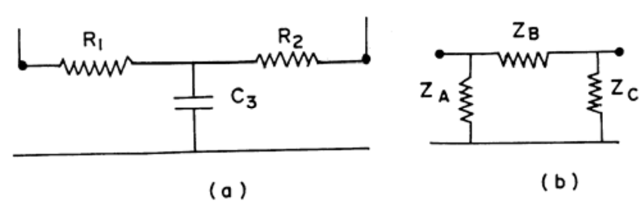

Fig. 1— a) Schematic diagram of RC network (T-Type) for an inductor. (R_1 and R_2 are thin film resistors and C_3 is a precision capacitor; b) Equivalent network of the above T-network with Z_a, Z_b and Z_c as the branch impedances

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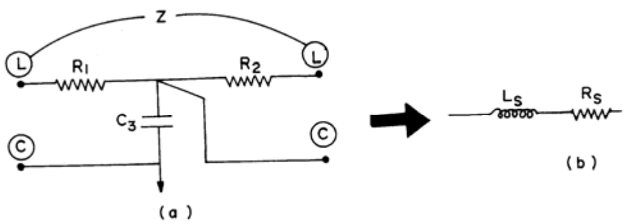


Fig. 2— a) Basic circuit of 4-TP inductance standard; and b) Its equivalent circuit

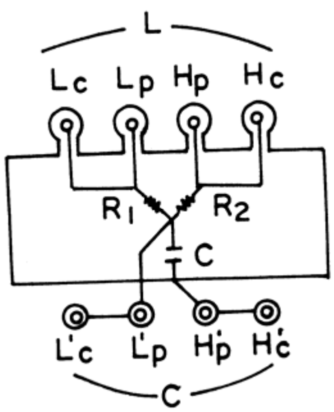


Fig. 3— Schematic diagram of internal construction of 4-TP standard inductor

Table 1— Nominal values of R_1, R_2 and C_3 chosen to construct the 4-TP inductance standards of various nominal values

Inductor nominal value, μH	Resistor, R_1 Ω	Resistor, R_2 Ω	Capacitor, C_3 pF
10	100	100	1000
100	316	316	1000
1000	1000	1000	1000

Since these types of standard inductors are not available commercially, so a set of 4-TP inductance standards (10 μH, 100 μH and 1000 μH) has been designed and developed. This paper discusses various aspects involved in the design and development of such inductors. The application of these inductors for their use as echelon I level transfer standards and for calibration of 4-TP LCR meters/impedance bridges have also been given.

High Frequency Standard Inductors

Circuit and Design

The relation for circuit impedance (Z) in 4-TP inductance standards (Fig. 2a) is obtained as:

$$Z = R_1 + R_2 + jw\, R_1\, R_2\, C_3 \qquad (3)$$

whereas its equivalent circuit (Fig. 2b) comprises of inductance L_s and resistance R_s in series as

$$R_s = R_1 + R_2 \qquad \ldots(4)$$

$$L_s = R_1\, R_2\, C_3 \qquad \ldots(5)$$

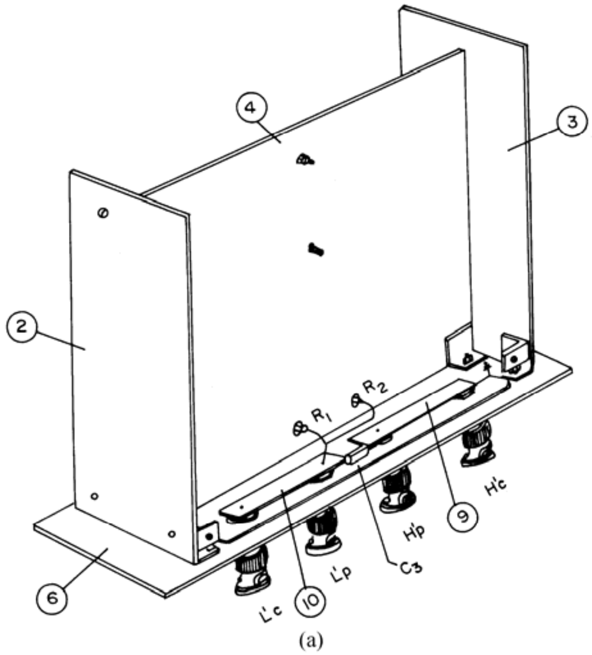
However, the standard value of inductance can be computed using Eq. (5). When R_1 and R_2 are given in ohms and C_3 in *pF*, then L_s is obtained in henry. Hence while designing the inductance standard, the values of R_1, R_2 and C_3 are to be chosen judiciously so as to obtain the standard inductor of the required nominal value (Table 1). Also, while computing the standard value of inductance, it is desirable for practical purposes, to include for compensation of the stray capacitance associated with the BNC terminals; which is 7.1 *pF* for the present case. As such Eq.(5) modifies to:

$$L = R_1\, R_2\, (C_3 - 7.1pF) \text{ henry} \qquad \ldots(6)$$

In the internal construction of the inductance standard (Fig. 3), R_1 and R_2 are thin film resistors and C_3 is a capacitor. The terminal L_c, L_p, H_c and H_p are provided with BNC connectors to form 4-TP configuration. Fig. 4a shows the left hand side view and Fig. 4b shows the right hand side view with shielding cover removed. Resistors R_1, R_2 and capacitor C_3 in the form of RC circuit (Fig. 2a) have been fitted inside an aluminum box (12cm x 5cm x 9cm); the front plate of which is provided with the 2 sets of four BNC connectors. The center plates have been provided in the box to serve as shield between the different components (R_1, R_2 and C_3). However, the shielding cover takes care of the outside stray fields. The two copper plates (thickness, 1 mm), which are provided to join current and potential terminals, ensure low resistance path between the terminals. The accuracy of inductors thus designed is ± 0.05%.

Results and Discussion

The 4-TP configuration inductors are best suited for calibration of multi-frequency LCR meters/ impedance bridges having 4-TP configuration; because in that case good compatibility between the instrument under calibration and the standard is achieved. Moreover, this would also minimize the effects of residuals associated with cabling and connection. As such, using these inductance standards, a multi-frequency LCR meter (accuracies, 0.1-3 %) have been calibrated at different frequencies between 10 kHz and 3 MHz for spot nominal inductance values of 10 μH, 100 μH and 1000 μH



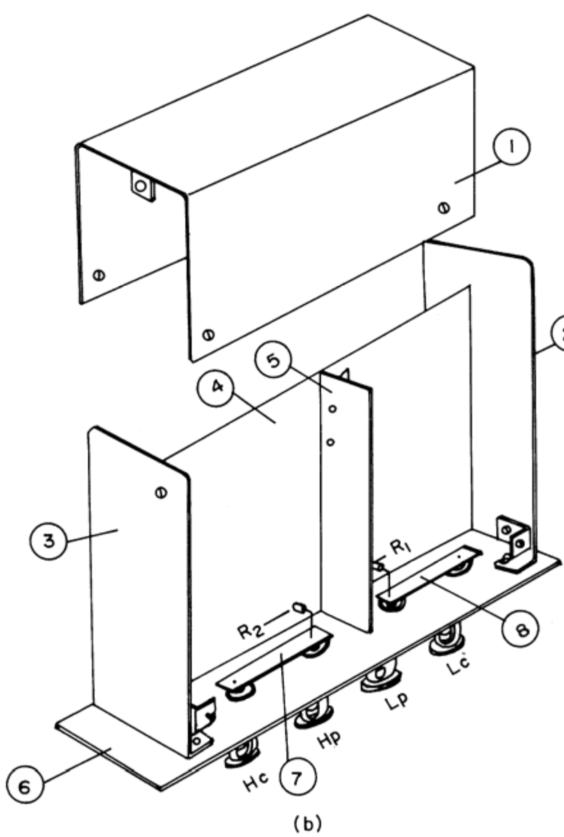


Fig. 4— a) Left side view of the inside of 4-TP standard inductor; b) Right side view of the inside of 4-TP standard inductor with shielding cover removed. 1: Shielding cover; 2 &3: Side plates; 4: Centre plate; 5: Shielding plate; 6: Front plate; 7-10: Copper strips; C: Capacitor; R_1, R_2: Thin film resistors; L'_c L'_p H'_c, H'_p : BNC Connectors; and L_c L_p H_c H_p: BNC connectors.

Table 2— Calibration of multi-frequency LCR meter using the HF standard inductors

Frequency	Measured inductance value		
	Inductor (10 μH) μH	Inductor (100 μH) μH	Inductor (1 mH) mH
10 kHz	10.21	101.6	1.061
30 kHz	10.23	101.8	1.061
100 kHz	10.23	101.0	1.061
300 kHz	10.23	101.2	1.061
1 MHz	10.20	101.2	1.064
3 MHz	10.31	102.0	1.074

(Table 2). Further to confirm the validity of the measured inductance values (L_m), they have been compared with their computed values (L_c), which are obtained by measuring R_1, R_2, and C_3 by using high accuracy resistance/capacitance meters and subsequently computing the inductance value (L_c) by employing Eq. (6). For example, to measure 10 μH inductor at 30 kHz, Table 2 gives that its mean measured values (L_m) is 10.23 μH, with measurement uncertainty of ± 0.03 μH. Further the resistors R_1, R_2 and capacitor C_3 of the 10 μH inductor are measured at 30 kHz. The measured values obtained are: R_1 = 99.65 Ω, R_2 = 99.70 Ω and C_3 = 1035.98 pF. The uncertainty for resistance measurement is ± 0.01% and for capacitance is ± 0.03%. Now employing Eq. (6), one finds the computed value (L_c) obtained is 10.222 μH ± 0.005 μH. This shows that the measured and computed inductance values agree within their limits of uncertainty. Thus analysis of the results confirms the feasibility of the approach and also better accuracy impedance bridges can be calibrated using the HF standard inductors thus designed and developed at NPL.

Conclusions

A set of 4-TP high frequency standard inductors (10 μH, 100 μH and 1000 μH) has been designed and developed. These inductors use thin film resistors and high quality capacitors, which show little variation at HF. Also, their 4-TP configuration helps to minimize residual impedances and stray field effects at HF. So their inductance values vary little at high frequencies upto about 10 MHz. As such these inductors can serve as Echelon I level transfer standards at HF and are also quite suitable for calibration of 4-TP LCR meters/impedance bridges.

Acknowledgements

Authors thank Dr P C Kothari, NPL, for constant encouragement, and Director, NPL for permission to publish this paper.

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