# Low Temperature Magnetic Properties of Metglas 2714A and its Potential Use as Core Material for EMI Filters

**Hung P. Quach and Talso C. P. Chui***

*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 79-24, Pasadena, CA 91109, USA*

## ABSTRACT:

Inductive filters against electromagnetic interference (EMI) are commonly made by winding coils around a magnetic material with high permeability. This permeability should remain high at high frequencies, so that the impedance of the inductor made from it can be large to block off any high frequency EMI signals. Room temperature magnetic material like ferrite loses most of its permeability at low temperatures. Some low temperature materials like Cryoperm-10 are known to have high magnetic permeability. But the permeability of all of them decreases to a low value at frequencies higher than a few hundred hertz due to eddy current shielding of the magnetic field. We have measured the complex relative permeability of Metglas 2714A (also known as Magnaperm) at 4.2 K, and found that its magnitude is larger than 10,000 at frequencies up to 100 kHz. We also measured the magnetization noise density from this material using a SQUID magnetometer. We find that the noise density agrees well with the predictions of the fluctuation dissipation theorem. This implies that low temperature inductors and transformers with predictable noise characteristics can be designed for applications where the lowest noise is not a limiting factor of performance. For very low noise applications, common mode filter can be made with this material, where the two input leads to a pre-amplifier is wound as a pair around the material, so that any magnetization noise is cancelled out.

* Tel: +1-818-354-3104; fax: +1-818-393-3707.
*E-mail address*: Talso.C.Chui@jpl.nasa.gov (T.C.P. Chui)

## I. INTRODUCTION:

Low noise measurements are often performed at low temperatures because of the reduced thermal noise and the availability of high sensitivity sensors like the superconducting quantum interference device (SQUID) for the measurement. These measurements are extremely sensitive to electromagnetic interference (EMI) because of their low noise and high sensitivity nature. Yet, commonly used room temperature inductive filters are ineffective at low temperatures because all known magnetic core materials in these filters lose most of their permeability at low temperatures. For example, the relative permeability $\mu_r$ of ferrites decreases from a value of ~10,000 at room temperature to a value of ~20 at 4.2 K. In this paper, we report the evaluation of two materials – Cryoperm-10 [1] and Metglas 2714A [2] - at 4.2 K to assess their usefulness as core materials for low temperature inductive EMI filters. Cryoperm-10 is commonly used as magnetic shielding material for low temperature applications because it is known to have $\mu_r$ in excess of 10,000 at 4.2 K. However, its usefulness as magnetic core material needs to be proven. Cryoperm-10 is available commercially in sheets of 0.5 mm or thicker. We found that Cryoperm-10 in the currently commercially available form is not suitable for an EMI filter due to eddy current, which reduces $\mu_r$ to a low value at frequency >100 Hz. For a good EMI filter, $\mu_r$ needs to maintain its high value at high frequencies so that the impedance of the inductor wound on it remains high to block the flow of high frequency EMI signals. On the other hand, Metglas has a very high $\mu_r$ of >10,000 at room temperature with unknown properties at 4.2 K. It is available commercially in the form of tape wound toroidal cores, with an inner core diameter of 8 mm or larger. The thickness of the tape in the core is 18 $\mu$m. We found that $\mu_r$ >10,000 at 4.2 K and at frequencies up to 100 kHz, which is the limit of our measurement capability. The problem associated with eddy current is apparently mitigated by the thinness of the tape. Therefore, Metglas 2714A should be a good material for low temperature EMI filters. However, our measurement indicated a large magnetization noise from the core, which agrees well with the predictions of the fluctuation dissipation theorem. Therefore, for very low noise applications, this material is only usable as a common mode filter, where the two input leads are wound as a pair on the magnetic core so that any noise from the core is cancelled out.

A large volume of literature already exists on the permeability and magnetization noise of magnetic materials at low temperatures. For example, Vitale *et al* studied the thermal magnetic noise in rf SQUIDS coupled to a transformer with Cryoperm-10 core [3]. Prodi *et al* reported similar measurements of a family of Co-Mn-based alloy called VITROVAC [4]. Durin *et al* discussed the origin of 1/f thermal noise in 14 different soft magnetic materials [5]. These studies focused on understanding the origins of magnetization noise from magnetic materials, with an aim of finding low noise material for building low temperature transformers. All of these papers reported that the magnetization noise is in good agreement with the fluctuation dissipation theorem, confirming its thermal origin. All of the materials reported are not suitable for use as EMI filters in their existing forms, because all have low permeability at frequencies larger than a few hundred hertz. The lack of suitable material has motivated us to perform new studies on a different material.

## II. EXPERIMENTAL METHODS

The method for measuring the permeability and noise is similar to that reported by Vitale et al, which makes use of the conservation of flux in a superconducting loop. The measurement circuit is shown in Figure 1. Two single turn coils are wound around a torus. A sinusoidal current is injected into Coil 1, while a DC SQUID detects the induced superconducting current in Coil 2. The output of the DC SQUID is connected to a lock-in amplifier for phase sensitive detection. Let $I_s$ be the current induced in Coil 2 by the current $I$ in Coil 1. Let $L$ be the inductance of both Coil 1 and Coil 2, and $L_s$ be the inductance of the SQUID input coil. The total flux that threads through the toroid is given by $\Phi_T = L(I - I_s)$. Since the flux through the SQUID's superconducting pickup loop is conserved, the same amount of flux in the opposite direction must be induced into the SQUID pickup coil. Thus $\Phi_T = L_s I_s$. Solving these two equations gives:

$$L = L_s I_s / (I - I_s) \tag{1}$$

The inductance of the SQUID was given by the manufacturer as $L_s$ = 1.86 μH. However, this value gives a noticeable disagreement between the measured magnetization noise density and the noise density computed with the fluctuation dissipation theorem. To resolve the discrepancy, we developed a simple method for measuring $L_s$ and found that $L_s$ = 1.573 μH, which is 85% of the manufacturer's value. Details of this measurement are included in Appendix 1. The superconducting current $I_s$ is obtained from the output voltage of the SQUID controller, using the proportional constant given by the manufacturer. While this method is satisfactory at low frequencies, at high frequencies, the proportional constant varies with frequencies; also, there is an additional phase shift between the input and the output signals. The proper relation between the input current and the output voltage is $V = Z_s I_s$, where $Z_s$ is a complex transfer function, which must be determined in a separate experiment by measurements of $V$ and $I_s$ with a lock-in amplifier. With the measured transfer function, $I_s$ is determined from the output of the SQUID controller. With knowledge of both $I$ and $I_s$, Equation (1) would give $L$. The inductance of a toroidal coil is also given by $L = (\mu_r \mu_o N^2 d/2\pi)\ln(b/a)$, where $\mu_r$ is the relative permeability, $\mu_o$ = $4\pi$ x $10^{-7}$ henry/m is the permeability constant, $N$ is the number of turns around the torus, $d$ is the thickness of the torus, $b$ is the outer radius, and $a$ is the inner radius of the torus [6]. From Equations (1), we can determine the complex relative permeability $\mu_r$.

We have also measured the magnetization noise from the torus. The measurement circuit is shown in Figure 1. However, the output of the SQUID controller is connected to an analog to digital converter of a data acquisition board rather than to the input of the lock-in amplifier, and Coil 1 is disconnected from the lock-in amplifier signal drive. For this measurement, Coil 1 is in open circuit condition. Again, the transfer function $Z_s$ is used to convert the SQUID controller output voltage noise signal to the noise signal in $I_s$. The current noise density is computed using software supplied with the data acquisition system. It is then converted into units of $\Phi_o/\sqrt{Hz}$, where the flux quantum $\Phi_o = h/2e$ is $2.07\times10^{-15}$ Weber, $h$ is Planck's constant, $e$ is the electric charge of an electron. The conversion factor of 0.196 $\mu$A/$\Phi_0$ is given by the manufacturer, which we have verified independently to an accuracy of 1%.

According to the fluctuation-dissipation theorem, this measured noise density can be predicted from the measurement of the complex self-inductance $L$ of the coil wound around the torus. For any thermodynamic system, where work of the form $d(Work) = Fdx$ can be performed to the system by a generalized force $F$ and a gerneralized displacement $dx$, the power spectral density of $x$ is given by $PSD\_x = 4k_B T\,\mathrm{Im}[x(\omega)/F(\omega)]/\omega$, where $\omega$ is the angular frequency [7]. For the circuit in Figure 1, $d(Work) = -I_s(L_s + L)dI_s$, so

$$PSD\_I_s = \frac{-4k_B T}{\omega} \mathrm{Im}\left[\frac{1}{L_s + L(\omega)}\right]. \quad (2)$$

We expect that there is comparatively little loss in the SQUID; therefore, we assume that $L_s$ is real and that all the imaginary part arises from $L(\omega)$.

Since the permeability and the magnetization noise density of Cryoperm-10 have already been well characterized, re-measurement of this material can be used to verify our measurement and data analysis techniques [3]. After we are satisfied with our techniques, we then make measurements with Metglas 2714A. However, the permeability of Metglas remains high at frequencies higher than 20 kHz, which is the maximum usable frequency in the flux-lock-loop mode of SQUID operation. For the Metglas measurement, we switched to the open-loop mode of SQUID operation, so that we can make measurements up to 100 kHz. The magnitude of the transfer function of the SQUID controller is shown in Figure 2 for both the open-loop mode and the flux-lock-loop mode.

In the following section, we present measurements of the complex permeability of both Cryoperm-10 and Metglas 2714A. The measured flux noise density is also compared to the prediction of the fluctuation dissipation theorem.

## III. RESULTS

We have performed measurements on two toroidal cores. The dimensions of the Metglas 2714A torus is a = 4.75 mm, b = 6.23 mm, and d = 4.94 mm. The dimensions of the Cryoperm-10 torus is a = 0.755 mm, b = 1.455 mm, d = 1.55 mm. Figures 3a and 3b show plots of the real and the imaginary parts of $\mu_r$ respectively at 4.2 K. The data was collected in the frequency ranging from 1Hz to 100 kHz for Metglas 2714A, and in the frequency ranging from 1 Hz to 20 kHz for Cryoperm-10. The real part of $\mu_r$ is consistently above 10,000 for Metglas 2714A. For Cryoperm-10, $\mu_r$ >16,000 at low frequencies. However, it has a steep roll-off at approximately ~100 Hz. This roll-off is a result of eddy current shielding inside the torus. The imaginary part of $\mu_r$ is negative. For Metglas 2714A, its magnitude is less than 1,000 and is almost independent of the frequency. The drop at frequencies higher than 10 kHz is most likely caused by the uncertainties of the large correction of the SQUID transfer function and therefore is not likely to be the property of the material. For Cryoperm-10, the magnitude of the imaginary part of $\mu_r$ is much larger than 1,000 with considerable variations over the frequency range of 10 Hz to 10 kHz. The relatively small value of $\mathrm{Im}(|\mu_r|)$ for Metglas 2714A can be interpreted as low energy loss compared to Cryoperm-10.

For comparisons of the effectiveness of Metglas 2714A and Cryoperm-10 as EMI filters, we have computed the impedance of a one turn coil using the formula $Z = i\omega L$, using the measured values of $\mu_r$ and the geometry of the Cryoperm-10 torus (a = 0.755 mm, b = 1.455 mm, d = 1.55 mm) for computing $L$. The magnitudes of Z are plotted in Figure 4. It is clear from this plot that $|Z|$ for Cryoperm-10 saturates at a relatively low value of $|Z| \approx 10^{-3}\,\Omega$, while Z for Metglas 2714A continues to rise at high frequencies to a value of $|Z| \approx 2.5\ \Omega$ at 100 kHz.

The magnetization noise measurements for Metglas 2714A and Cryoperm-10 at 4.2 K are shown in Figure 5a and 5b respectively. The solid line is the measured noise density, which is the square root of the power spectral density. The dotted line is the prediction of the fluctuation dissipation theorem with no adjustable parameters. The dashed line in Figure 5a shows the measured SQUID noise density. There is a sharp drop of the measured noise density for Metglas at 50 kHz due to the anti-alias filter used in the measurement. Therefore, this drop is not the property of the material. The excellent agreement between theory and measurement verified the measurement and data analysis techniques reported in this paper.

## IV. CONCLUSION

According to our measurements, Metglas 2714A should be an excellent material for inductive low temperature EMI filter. At liquid helium temperatures, it has a relative permeability $\mu_r > 10{,}000$ at frequencies of up to 100 kHz. For comparison, Cryoperm-10 may have a higher relative permeability, $\mu_r > 16{,}000$ at 4.2 K, but $\mu_r$ begins to roll off at about 100 Hz due to eddy current. Moreover, our noise density measurements of Metglas 2714A are in good agreement with the prediction of the fluctuation dissipation theorem. This implies that inductors and transformers with predictable noise characteristics can be designed for various applications.

It would be desirable to have data for Metglas 2714A at frequencies higher than 100 kHz at low temperatures. This can be achieved by using a SQUID array amplifier that has an advertised bandwidth of 5 MHz and is available commercially [8]. At present, Metglas 2714A is available in sizes larger than 1 cm, which is rather large for EMI filter applications. An effort to miniaturize the torus is also desirable.

## VI. Acknowledgements

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## VI. Appendix: Measurement of the inductance of the SQUID input coil, $L_s$.

The inductance of the SQUID input coil, $L_s$, is measured by shunting the input coil with a small resistance $R$ of 0.871 Ω. As shown in Figure 6, an AC current $I$ is injected into the input coil of the SQUID with the shunt resistor. A portion of this current flows through the input coil. This portion is reported by the SQUID controller output as $I_s$. The resistor $R$ was made from a rectangular piece of copper-nickel with superconducting leads attached to it. The resistance value was accurately measured at 4.2 K using a four-terminal measurement technique. All wire contacts in Figure 6 are superconducting to avoid contact resistance. It can be shown that $i\omega L_s I_S = (I - I_s)R$. If we let $A = I_S(\omega)/I(\omega)$, then

$$L_s = R(1 - A)/(i\omega A). \tag{3}$$

We measured $A$ using phase sensitive detection technique. Then $L_s$ can be determined with the measured $R$ and Eq. (3).

## REFERENCES

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[2] Metglas is a registered trademark and Magnaperm is a trademark of Honeywell International, Conway, SC 29526. Information available at http://www.eastern-components.com/pdf/Honeywell/ECI-502.pdf

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FIGURE CAPTIONS

Fig. 1. The measurement circuit.

Fig. 2. The measured SQUID transfer function. The solid line is for an open loop operation mode, and the dotted line is for a closed loop operation mode.

Fig. 3. a) The real part of $\mu_r$. b) The imaginary part of $\mu_r$. The solid line is for Metglas 2714A and the dotted line is for Cryoperm-10.

Fig. 4. The impedances of a one turn coil of the same geometry for Metglas 2714A (solid line) and for Cryoperm-10 (dotted line).

Fig. 5. The solid line is the measured noise spectrum for Cryoperm-10 and the dotted line is the prediction by the fluctuation-dissipation theorem for a) Metglas 2714A and b) Cryoperm-10. The dashed line is the SQUID noise.

FIG. 6 Circuit for measuring the inductance of the SQUID input coil.

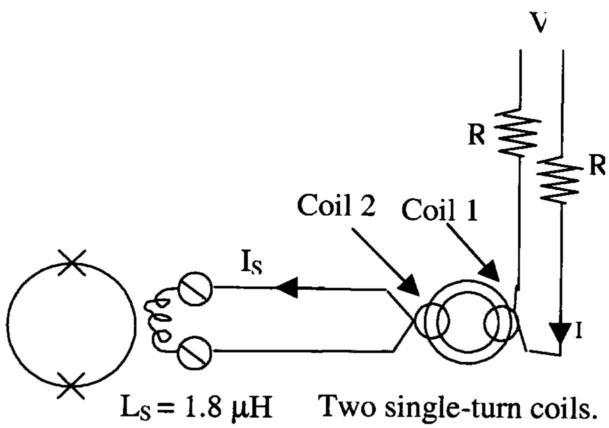
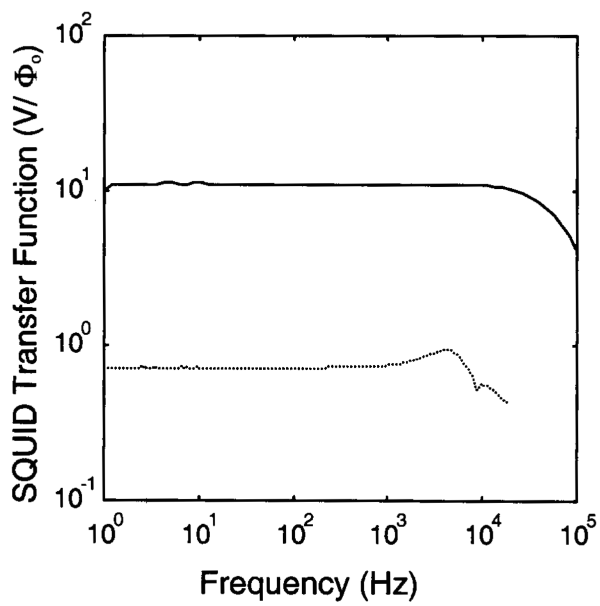



Fig. 1.



SQUID Transfer Function (V/ $\Phi_o$)
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
Frequency (Hz)


Fig. 2.

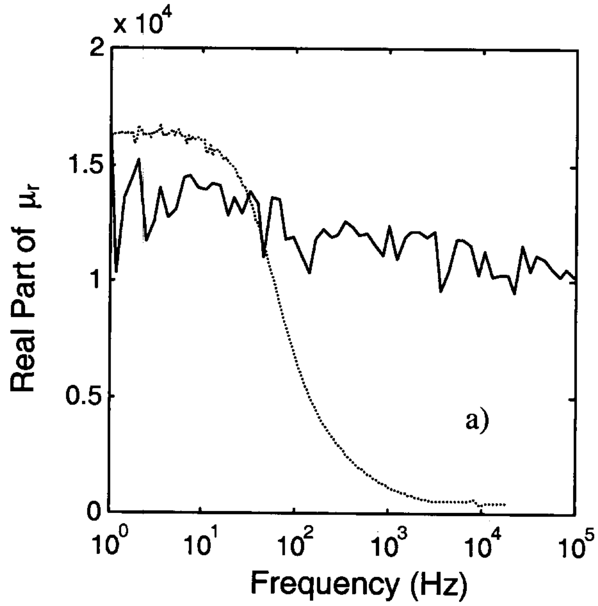

x 10^4
2
1.5
1
0.5
0
Real Part of μr
a)
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

Fig. 3a.

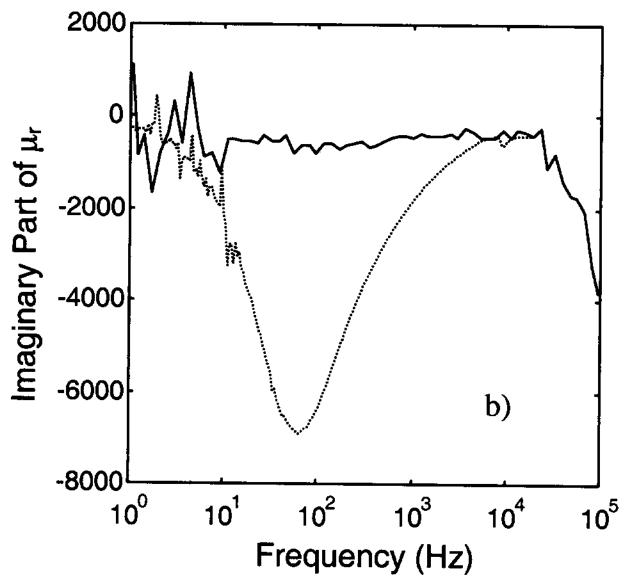

2000
0
-2000
-4000
-6000
-8000
Imaginary Part of $\mu_r$
b)
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
Frequency (Hz)

Fig. 3b.

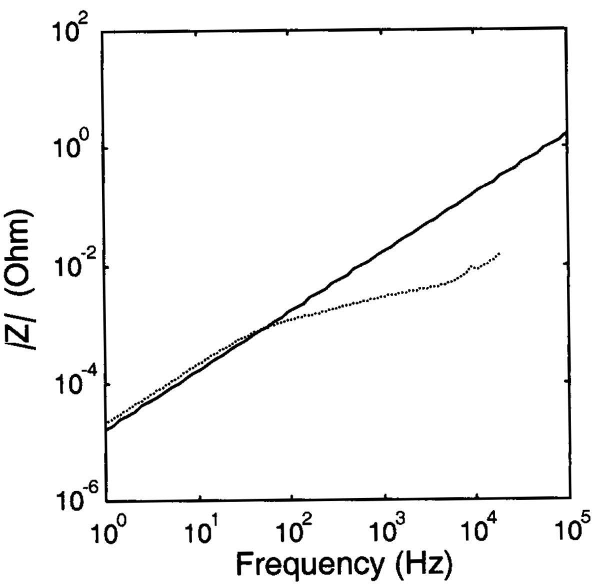



Fig. 4.

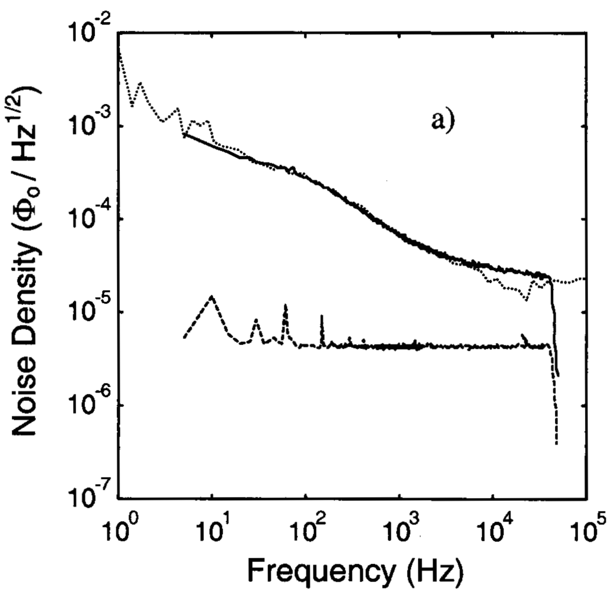

a)
Noise Density ($\Phi_o$ / Hz$^{1/2}$)
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
$10^{4}$
$10^{5}$
Frequency (Hz)

Fig. 5a.

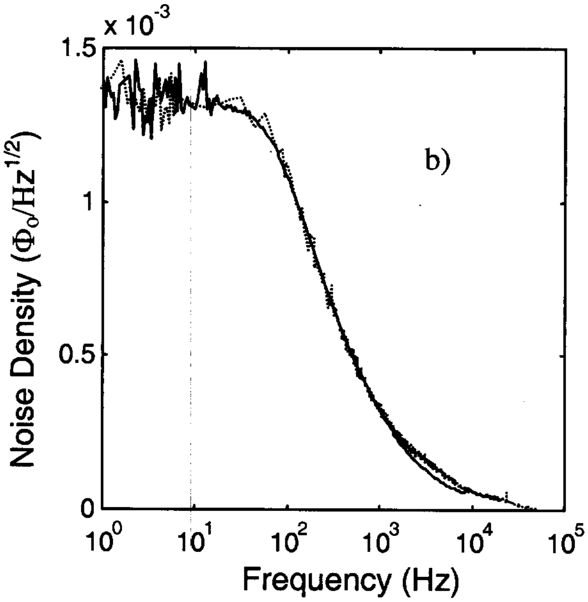

x 10^-3
1.5
1
0.5
0
Noise Density (Φ0/Hz^1/2)
b)
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

Fig. 5b.

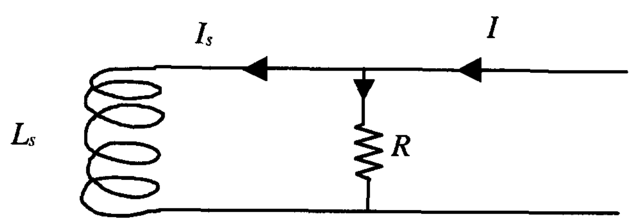



Fig. 6.