Technical Report

Wideband Transmission Transformer Technology In The Broadband Age

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1. Introduction

The trend in the communication fields such as the Internet, LAN (Local Area Network), and the like is moving increasingly quickly towards higher speed and high capacity communication. Against this background, there is a variety of developments in new transmission methods or ICs (integrated chips) accompanied by digitalization of transmission signals, and progress is notable. Of these, a wideband transmission transformer for communication is one of electronic devices essential to communication systems and required to deal with the notable progress.

Currently, there are a number of communication systems using wideband transmission transformers, but, herein, regarding transformers used two systems, Ethernet which is a LAN system and the ADSL which is a representative of high speed Internet communication, the most important design features of transmission characteristics, characteristics of the magnetic core material, the shape of the magnetic core and the winding structure will be described based on their purposes.

2. The role of the wideband transmission transformer

When designing a communication system using wires, it is first noted that communication terminals must be protected from unnecessary noise entering from the outside via the wires. However, electric fields and surges coming from power lines located at the periphery of communication systems such as Ethernet, ADSL, or the like generate noise. A transmission transformer is used to protect the communication terminal from the noise. Without a transformer, overcurrent flows directly into expensive communication terminals with their multiple ICs and so on, destroying semiconductor devices and the like. Generally, winding on the primary side and winding on the secondary side of the transformer are magnetically coupled, and a signal is transmitted through mutual induction. For DC current, the primary side and the secondary side are electrically insulated.

Also, for AC current, an overcurrent caused by noise does not flow to the secondary side since the magnetic core of the transformer is magnetically saturated. Wideband transmission transformers play an important role in communication systems in the broadband age because they can accurately transmit signals using their insulation functions, and, further, are low in price.

3. Transmission characteristics of wideband transmission transformers

Wideband transmission transformers used in Ethernet and ADSL are required to have characteristics which are considered not to have been greatly important in communication systems up to now because of the transmission methods. The DC superposition characteristics in Ethernet and the THD in ADSL are important characteristics. The two characteristics will be described later for each purpose.

In the meantime, wideband transmission transformers also have characteristics which have been conventionally considered important. The most important characteristic of these is insertion loss (also referred to as the amount of insertion attenuation).

Insertion loss

Insertion loss represents a loss (amount of attenuation), in dB units, when a signal is transmitted from the primary side to the secondary side, and it is important to have a low value over the entire frequency band utilized. The insertion loss in the transformer can be roughly expressed by the following equations (1) to (3) after three frequency ranges are substantially classified, from the simple equivalent circuit.

- Loss in the low frequency range

$$P_{loss(L)}=20\log\sqrt{1+\left(\frac{Z_1}{2\omega L_p}\right)^2} \quad \cdots\cdots\cdots\cdots (1)$$

- Loss in the intermediate frequency range

$$P_{loss(M)}=20\log\left(1+\frac{r_p+a^2r_s}{2Z_1}\right) \quad \cdots\cdots\cdots\cdots (2)$$

- Loss in the high frequency range

$$P_{loss(H)}=20\log\sqrt{1+\frac{\omega^2L_p{}^2(1-k)^2}{Z_1{}^2}} \quad \cdots\cdots\cdots\cdots (3)$$

Z_1: Line impedance
L_p: Inductance of coil
r_p, r_s: Primary and secondary coil resistances
$L_p(1\text{-}k)$: Leakage inductance
a: Turns ratio (N_p/N_s)

For the insertion loss in the transformer, the inductance of a coil is large in the low frequency range from equation (1), the resistance of a coil is small in the intermediate frequency range from equation (2), and the leakage inductance is small in the high frequency range from the equation (3), and, it is necessary to satisfy all conditions from the equations (1) to (3). If the shapes and winding structures of transformers are the same as each other, in order to manufacture a transformer with good wideband transmission characteristics, it is a point to reduce the number of coil turns by using a magnetic core with high permeability.

4. Magnetic cores used for the wideband transmission transformer

As magnetic cores used for a transformer, there are soft magnetic materials such as metal materials, oxide magnetic materials, or the like; however, oxide magnetic materials, called ferrites, are mainly employed in a transformer used over the wide frequency band in order to utilize the frequency characteristic.

Kinds and applications of the ferrite are shown in Table 1[*1)]. The wideband transmission transformer herein generally employs a soft magnetic material, called a MnZn ferrite, in consideration of the transmission method, since MnZn ferrite has a high permeability, a low-loss, and a high saturation magnetic flux density even at a high temperature at a relatively high frequency.

On the fundamental characteristics of the magnetic core

Material characteristics of the magnetic core include fundamental characteristics such as initial permeability and B-H characteristics. The characteristics will be described with reference to Figure 1.

Figure 1 Fundamental characteristics of the magnetic core

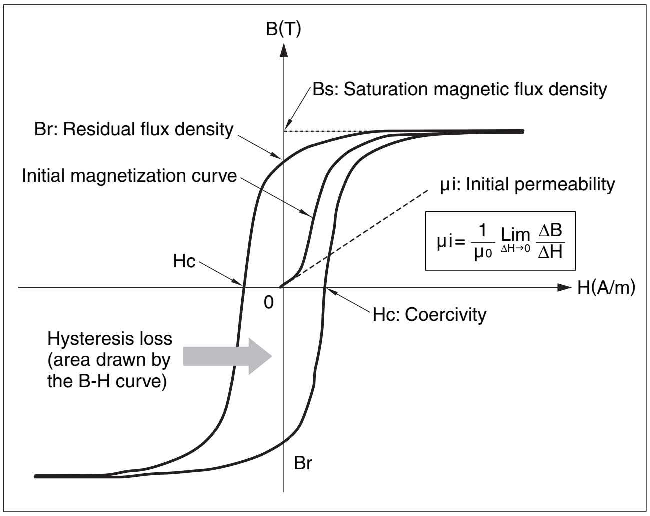

Figure 1 shows variations in magnetic flux in the magnetic core when coils are wound on the magnetic core and currents flow in the coils to generate a magnetic field, which is generally called a B-H loop (or B-H curve). The initial permeability indicates variations in the magnetic flux to variation in the tiny magnetic field (in the reversible magnetization range) in the vicinity of the origin in the initial magnetization curve in the B-H loop, which indicates the responsiveness with respect to the external magnetic field of the magnetic core, and it is an important characteristic of a ferrite used for communication.

Table 1 Kinds and applications of the ferrites

Applications	Used frequency	Kinds of magnetic cores	Shape	Necessary characteristics
Telecommunication	1k to 1MHz 0.5M to 80MHz	MnZn ferrite NiZn ferrite	Toroidal, E shape Pot type	High permeability Low temperature coefficient
Switching power supply	25k to 1MHz	MnZn ferrite	E shape	Low loss High saturation magnetic flux density
Fly-back transformer	16k to 65kHz	MnZn ferrite	U shape	Low loss High saturation magnetic flux density
Filter	1k to 500kHz 0.1M to 300MHz	MnZn ferrite NiZn ferrite	FT type, ET type Drum type	High permeability, High impedance
Magnetic head	1k to 10MHz	MnZn ferrite		High density, High permeability
Deflection yoke	16k to 65kHz	MgZn ferrite	Bosh type	High resistance, Dimension accuracy, Low loss
Sensor		MnZnCu ferrite	Toroidal	Fine control of Curie temperature

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By using a magnetic core with high initial permeability, it is possible to fabricate a transformer having a high inductance per each turn of the coil. When the magnetic field (current) is increased further than the level of the initial permeability, the magnetic flux in the magnetic core is also increased, but a saturation phenomenon occurs at a certain constant value. The magnetic flux density at this time is referred to as the saturation magnetic flux density and is indicated by Bs(T).

Next, by gradually decreasing the magnetic field from the saturation state, its level becomes 0(A/m) again, and, the magnetic flux density at this time is referred to as the residual flux density, which is indicated by Br(T). In addition, when the magnetic field varies towards the negative side and the magnetic flux density becomes 0(T), the field intensity at this point is referred to as the coercivity, which is indicated by Hc(A/m).

Further, a loop drawn by a current variation of one cycle at the magnetic core is referred to as the B-H loop, and its area shows the loss. The area of the B-H loop is referred to as the hysteresis loss. If the magnetic flux is saturated in an actual transformer, overcurrent flows therein, and thus its level is designed not to be saturated, so the area becomes smaller. However, since the hysteresis loss increases in proportion to driving frequency, it is an important characteristic and has great influence on a communication transformer, or a power transformer and a fly-back transformer requiring good efficiency in the high frequency.

5. Wideband Transmission Transformer In The Ethernet

5-1. Ethernet transmission method

As a standard of the LAN for connecting servers, printers, or computers to one another, there is Ethernet (IEEE802.3). Ethernet is currently used as a LAN system in a wide variety of fields. 10BASE5 was standardized in 1983, and thereafter, Fast Ethernet (100BASE-T) was standardized due to acceleration of communication speeds in 1995. At present, this 100BASE-T is prevailing in the market, but 1000BASE, 10 gigabit Ethernet with higher speeds are likely to be standardized. 10BASE-T and 100BASE-T have different transmission speeds and methods from each other, and the characteristics required for the transformers are also different. This article describes a wideband transmission transformer (pulse transformer) to be mounted on 100BASE-T.

Figure 2 shows a configuration of a NIC (Network Interface Card) as an example of a system of the 100BASE-T standard. In addition, a simple circuit diagram of the transmission transformer is shown in Figure 3.

Figure 2 Configuration diagram of NIC (Network Interface Card)

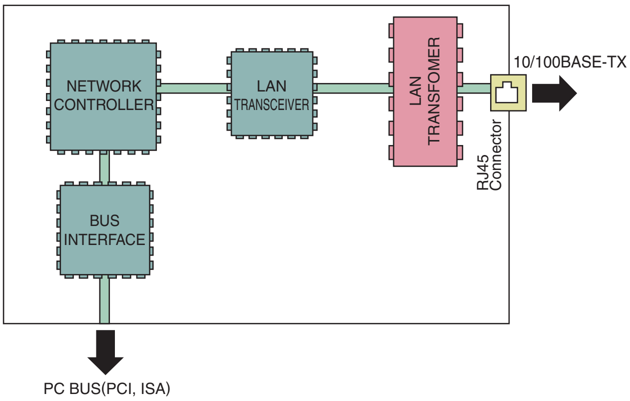
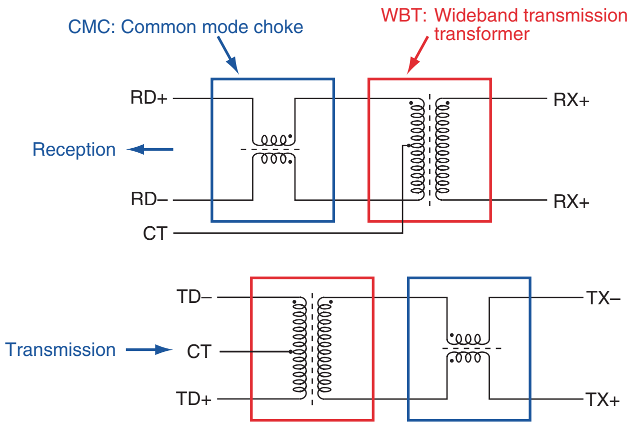


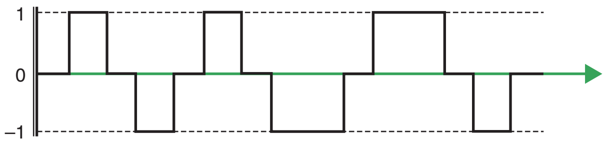
Figure 3 Circuit diagram of LAN transformer



The 100BASE-T performs transmission and reception of signals by an access control method called CSMA/CD, and by having a UTP cable (category 5) as the transmission medium, via an RJ-45 connector.
The frequency band which is used ranges from 0.1 to 100MHz (5 to 10MHz in 10BASE-T), and, in the same manner, characteristics in that frequency band are required for the transformer. The transmission method of 100BASE-T is performed by a baseband transmission method, but 4B/5B encoding, in which 4-bit data is converted into 5-bit data, is performed for the transmitted signal which is then converted into a serial signal using NRZI (Non Return to Zero Inversion) encoding.

The signal additionally returns to an NRZ signal, and undergoes a randomization process by scrambling using MLT-3 (Multi Level Transmission) encoding so as to be transmitted. A signal waveform of MLT-3 is shown in Figure 4[*2,3]. Such a baseband transmission has a problem in that the baseline is varied in the reception side.

Figure 4 A signal model of the MLT-3



A model of the baseline variation is shown in Figure 5. Figure 5(a) shows a transmission waveform when a single polarity pulse train with the amplitude A and the duty ratio 0.5 is changed from a continual space pattern to a continual mark pattern. Figure 5(b) shows a reception waveform corresponding thereto. After the pattern is changed as such, the effective pulse amplitude approaches A/2 and the baseline approaches -A/2 as time elapses[*4]. This baseline variation alters a bias in the transformer. When the inductance is extremely reduced due to variations in the bias in the transformer, there is a case where the reception side cannot detect the signal. For this reason, DC superposition characteristics are important to the transformer. Ethernet (100BASE-T) is specified having a maximum bias of 8mA, which is the worst case under the ANSI standard.

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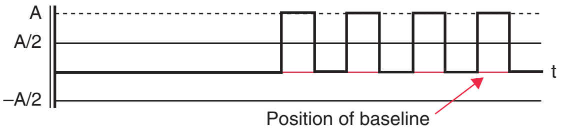
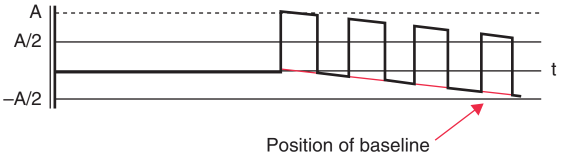
Figure 5

(a) Transmission pulse train



(b) Reception pulse train



5-2. Important characteristics of a wideband transmission transformer for Ethernet

The characteristics required for a transmission transformer with Ethernet (100BASE-T) are determined by the IEEE802.3 standard and ANSI as follows.

DC superposition characteristic:
L_{DC}(μH)≧350μH(100kHz, 100mV, DC=8mA)
Variation rate: (L_{DC})≧(1/2)×L_0
Withstanding voltage: AC.1500Vrms/1min
L_{DC}: Inductance at the DC superposition(DC=8mA)
L_0: Inductance at no load (DC=0mA)

In addition to the above described standards, the transmission characteristics generally require the following specifications.
Insertion loss: –1dB max.
L_0: 100kHz, 100mV at 25°C
Allowable temperature range of L_{DC}:
0 to +70°C or –40 to +85°C

5-3. On the DC superposition characteristic and the temperature range

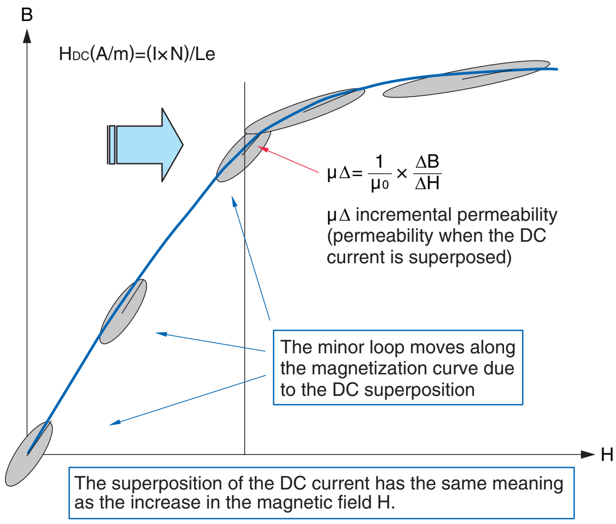
When designing a transformer for Ethernet, the DC superposition characteristic (inductance characteristics when the DC is superposed) is important in consideration of the transmission method as described above.
The DC superposition characteristic means a characteristic indicating the relationship between bias current and inductance when a DC bias is loaded to the base of an AC signal, and it is said as “the DC superposition characteristic is good” when the inductance is high even though the bias current is increased.

The DC superposition characteristic of a transformer using the ferrite core is described based on the magnetization curve of the B-H loop. The model is shown in Figure 6. The typical transmission transformer is required to have a high permeability (initial permeability) in the vicinity of the origin of the B-H loop as a magnetic core. However, there is a case where a DC current of 8mA is superposed, as in a transformer for 100BASE-T.
The DC superposition means that the center of the minor loop (a tiny B-H loop formed by the AC signal) moves along the magnetization curve from the origin as in Figure 5.

For this reason, the slope of the minor loop can maintain a constant value when the current increases to a certain current value (external magnetic field) (the transformer maintains a constant inductance characteristic with respect to variations in the bias current (refer to Figure 8)).

However, if passing the regions, magnetic saturation starts and thus the slope of the minor loop decreases (inductance of the transformer is steeply reduced).
As such, the permeability of the magnetic core in a case where the DC current is superposed on the base of the AC signal is different from the initial permeability, which is referred to as an incremental permeability (indicated by μΔ), and is expressed by the equation in Figure 6.

Figure 6 Diagram illustrating the DC superposition in the B-H loop

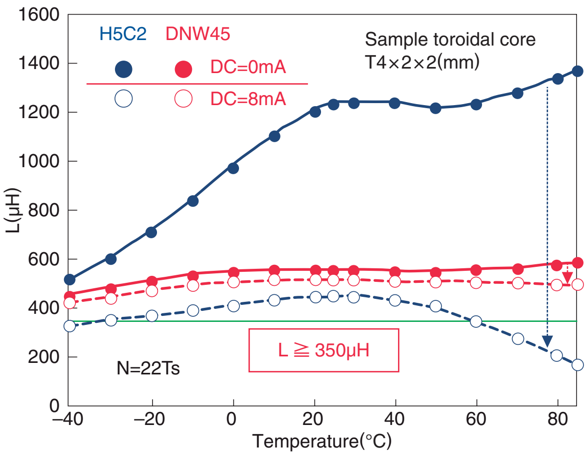


The DC superposition characteristic additionally has temperature characteristic which must be good over the usage temperature range. Ethernet generally has two kinds of specifications depending on usage temperature environments. One is used in a range of 0 to +70°C, which is specification typical for indoor mounted PCs, hubs, switches, and routers. The other is used in a range of –40 to +85°C, which is a specification applied to devices mounted in places where temperature environments are severe. This is mainly for industry and is used for a LAN for production management or equipment control.
As described above, it is important to select a transformer having a good DC superposition characteristic and a high inductance in the temperature range based on its purpose.

5-4. On the magnetic core materials for a transformer having a good DC superposition characteristic

Conventionally, the wideband transmission transformer used for ISDN or the like has used a material (material having a high initial permeability (μi)) having a high inductance at the initial permeability level in the magnetic core, and there was no specification such as the DC superposition. Thereby, Figure 7 shows temperature characteristics of initial permeability and temperature characteristic (–40 to +85°C) when a DC current is superposed, in a case where a small toroidal transformer is manufactured using such a magnetic core material (H5C2: μi=10000) and in a case where it is manufactured using a magnetic core material (DNW45: μi=4200) for 100BASE-T.

Figure 7 Temperature characteristics at the initial permeability and the DC superposition



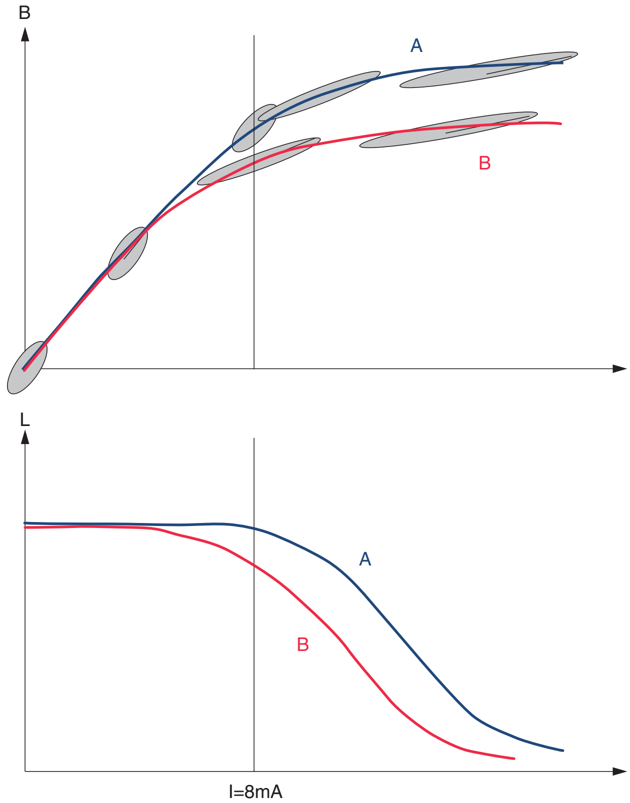
It can be seen from the figure that H5C2 has a very high inductance characteristic when the DC current is not superposed, but has extremely reduced inductance when the DC current is superposed, and particularly, does not satisfy the ANSI standard (L≧350μH) on the high temperature side. On the contrary, it can be seen that DNW45 maintains a relatively high inductance (L≧350μH) in both cases where a DC current is superposed and where a DC current is not superposed.

From this, it can be found that the transformer using a conventional material with high initial permeability is not suitable for a transformer magnetic core for use with Ethernet. Therefore, hereinafter, which materials it is good to select will be described.

Influence of saturation magnetic flux density

First, a model of the influence of saturation magnetic flux density is shown in Figure 8. The magnetic cores A and B in Figure 8 have the same initial permeability and satisfy the relation of A>B in the saturation magnetic flux density Bs regarding the B-H characteristic.

Figure 8 Relationship between the saturation magnetic flux density and the DC superposition characteristic at the magnetic cores



When the DC current is superposed on the magnetic core (A in the figure) having a high saturation magnetic flux density, the magnetization curve is not easily saturated. Thereby, the inductance at the beginning (when the DC current is not superposed) is not reduced to maintain its value, so the DC superposition characteristic is good.

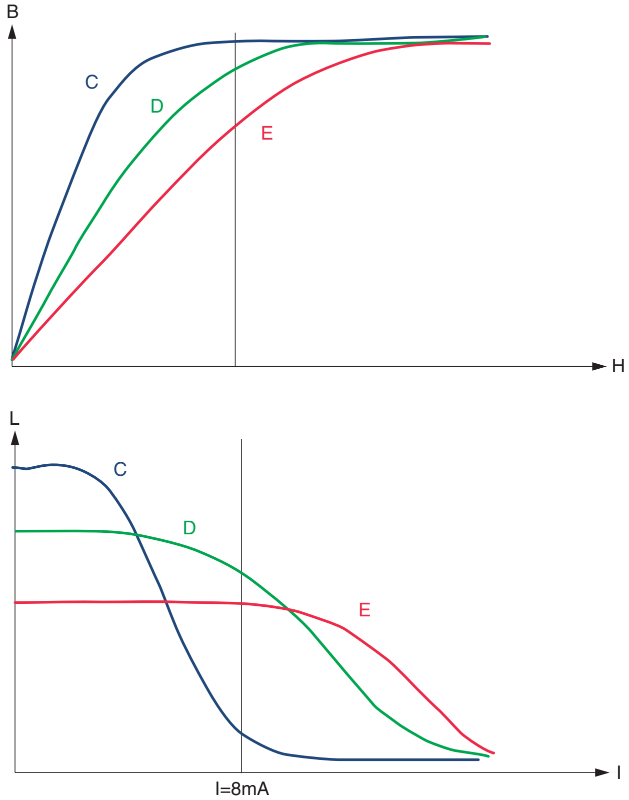
However, when the DC current is superposed on the magnetic core (B in the figure) having a low saturation magnetic flux density, the saturation phenomenon begins to occur at the magnetic core from a certain current value, and the slope of the magnetization curve decreases.

As a result, the DC superposition characteristic does not increase, and inductance is steeply reduced. Since, as the temperature characteristic of the saturation magnetic flux density, the inductance of the MnZn ferrite tends to be reduced with temperature increases the saturation magnetic flux density on high temperature side (driving signal generation circuit 70 to 85°C) becomes important.

Influence of the initial permeability

In addition, as shown in Figure 9, the DC superposition characteristic will be described in a case where transformers are fabricated using three kinds of magnetic cores C, D, and E which have the same saturation magnetic flux density, different initial permeabilities (initial permeabilities: C>D>E), and the same number of coil turns. For the magnetic coil C, initial inductance is very high, but inductance with respect to a DC magnetic field is rapidly reduced. For the magnetic coil E, variations in inductance with respect to a DC magnetic field are small and thus good, but the initial inductance characteristic is low. Therefore, it is preferable to select the magnetic core D (as an example) in which the balance between the initial inductance characteristic and the DC superposition characteristic is good.

Figure 9 Relationship between initial permeability and DC superposition characteristic in magnetic cores



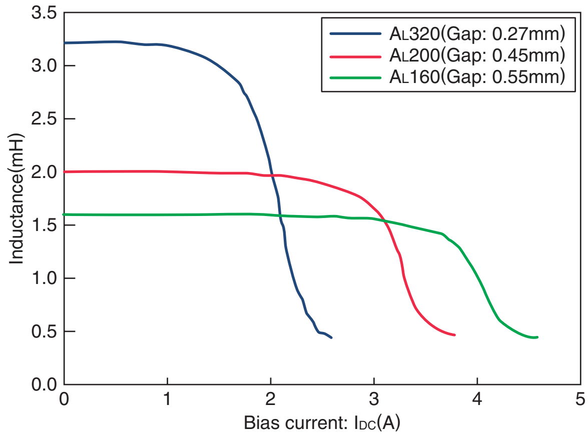
Selection of magnetic cores

It is thought that the DC superposition characteristic deteriorates in the MnZn ferrite H5C2 having high initial permeability described above since the high initial permeability is superposed on the low saturation magnetic flux density. It is important to select a balanced material having high saturation magnetic flux density and initial permeability the DC superposition characteristic at 70 to 85°C is sufficiently checked in consideration of the temperature characteristic of the saturation magnetic flux density in the MnZn ferrite.

5-5. An optimal shape of the wideband transmission transformer for Ethernet(100BASE-T)

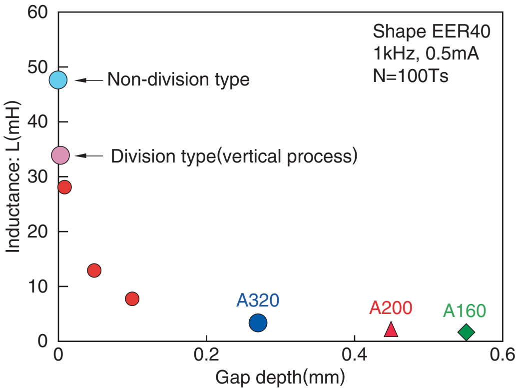
Next, it is the shape of transformers used with Ethernet that is important. Along with the small sizes and thinner profile of the latest communication terminals, electronic components mounted thereon are also required to have higher performance, and transmission transformers are no exception. As a measure for improving the DC superposition characteristic without increasing core size, there is the use of a transformer in which a gap is processed in a middle bridge of a typical division-type core (EE, EI, EER type, or the like). Figure 10 shows a detailed example of the relationship between the depth of the gap and the DC superposition characteristic.

Figure 10 Influence of gap in the DC superposition characteristic



It can be seen from the figure that the DC superposition characteristic improves as the processed amount (depth) in the gap process is increased. However, along therewith, the initial inductance also decreases. Also, in a non-division type toroidal shape, or “Closed magnetic circuit core” and “Square shaped closed magnetic core” shapes, and, even in the division-type where the gap process is not performed, the joined surface has a surface roughness due to a process, and an air gap (about 0.002mm) is generated in the fitting surface. For this reason, even though a transformer is fabricated using the division type having the same core constant and number of coil turns as the non-division type, the inductance is extremely reduced (refer to Figure 11).

Figure 11 Relationship between gap depth and inductance



Thereby, the division-type magnetic core shape is disadvantageous in terms of technology and cost because the number of coil turns is increased or a bobbin is used, or the like, in order to obtain the inductance. For the above reasons, generally, a transformer for Ethernet uses a non-division type small toroidal core. There is a case where its size has a limitation to the thickness (about 2.4mm) of a LAN card, and, typically, the core size mainly used has an outer appearance of 3mm to 5mm and a thickness of 0.7mm to 2.5mm. Further, since the MnZn ferrite has a low core resistivity, in order insulate a transformer, its surface is coated with an insulation coating such as paraxylene (typically called parylene) or the like, and winding is performed directly thereon to fabricate a transformer.

5-6. Design method of transformer

The design of the transformer is performed as described above, and, the magnetic field applied to the core due to the bias current of 8mA (the ANSI standard) can be obtained using the equation (4) if the core shape and the number of coil turns are determined.

$$H_{DC}=(I\times N)/l_e \qquad \cdots\cdots\cdots\cdots (4)$$

$$L=\frac{\mu_0\mu_\Delta\times N^2\times A_e}{l_e} \qquad \cdots\cdots\cdots\cdots (5)$$

H_{DC}: Applied magnetic field (A/m)
I: DC current (A)
N: the number of coil turns
l_e(m): Effective length of the magnetic core
A_e(m^2): Effective cross-sectional area of the magnetic core
$\mu_0=4\pi\times10^{-7}$
μ_Δ: Incremental permeability of the magnetic core (DC superposition characteristic)

$\mu\Delta$(incremental permeability) corresponding to the magnetic flux density obtained using the equation (4) is found in the material characteristic table, and it is confirmed whether or not a necessary inductance (350μH or more) is obtained using the equation (5).
By repeating this procedure, it is possible to obtain the outline of the necessary shape and number of coil turns.

It can be seen from the equation (4) that, in a case of magnetic cores having the same shape, the applied magnetic field increases in proportion to the number of coil turns. In addition, the inductance increases in proportion to the square of the number of coil turns from the equation (5). Therefore, there is a case where if the number of coil turns increases to obtain the inductance, the applied magnetic field becomes greater, and in turn the DC superposition characteristic deteriorates, and, conversely, inductance is decreased.

For this reason, it is important to set the core shape and the number of coil turns after fully understanding the material characteristics (particularly, on the low temperature side (–40, 0°C) and the high temperature side (70, 85°C) in the specification). Of course, the entire temperature range used is required to be considered.
It is ideal to design the transformer in order to maximally reduce the number of coil turns in consideration of reducing the insertion loss which is one of the important characteristics of the transformer initially described, and of cost of the transformer manufacture.

5-7. Winding method

The winding in the small toroidal for use in the 100BASE-T is performed in accordance with a winding method generally called a bifilar winding, thereby fabricating a transformer. The bifilar winding is a winding in which a primary winding and a secondary winding form a pair, and further decreases leakage inductance over independent windings, thereby contributing to improvement of transmission characteristics in the high frequency band.

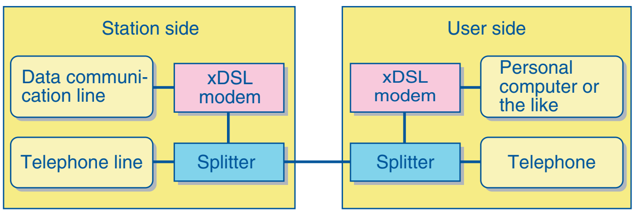
6. Wideband Transmission Transformer for ADSL Modem

6-1. Transmission method of ADSL

As an Internet system, xDSL (x Digital Subscriber Line) is the most prevalent. There is a case where it is said to be a transitional high-speed communication method until optical cable becomes widespread, and it has rapidly progressed since the year 2000 in Japan as well.
The xDSL has four types shown in Table 2 on the whole, but the major system in Japan is ADSL.
The communication method is advantageous in that existing telephone lines are available to reduce the infrastructure investment, and since a frequency band different from voice signals is used, telephone and data communication can be used at the same time. Up to now, the ADSL system has achieved a communication speed of about 10Mbps by using a frequency band of about 30kHz to 1.1MHz, and, recently, there is also a concept of a system which achieves high speed by using a frequency band of 2.2MHz or more, for higher speeds.

Figure 12 shows a schematic diagram of the transmission path of the ADSL system. ADSL uses a broadband transmission method which substantially includes two types, the CAP (Carrierless Amplitude Phase) method and the DMT (Discrete Multi Tone) method, and, herein, the DMT method is described.

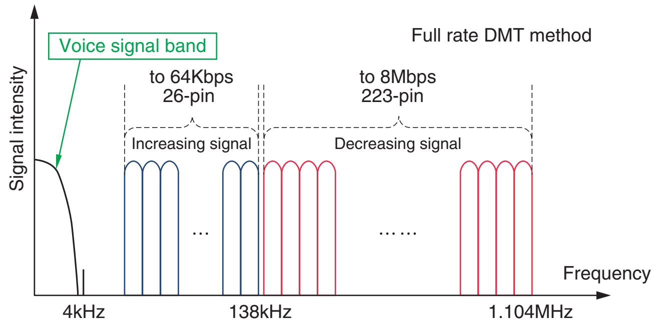
Figure 12 Schematic diagram of the ADSL system



In the ADSL system employing the DMT method, data is allocated to about 250 carriers (4kHz width) by the IFFT (Inverse Fast Fourier Transform: a digital signal is modulated to a tone signal), and is converted into analog signal using a D/A converter to be transmitted to the transmission path (telephone line) via a transformer.

On the reception end, the data is digitized by the A/D converter via the transformer and then is restored to the original data. The frequency spectrum in the DMT method is shown in Figure 13[*5,6)].

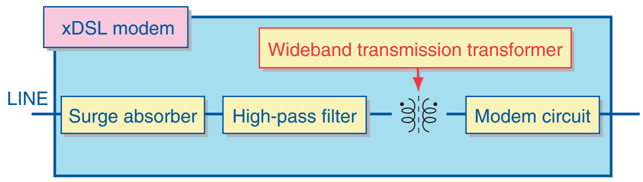
Figure 13 Frequency spectrum in the DMT



In addition, as shown in Figure 12, the signal transmitted from the telephone line is split into a voice signal and a data signal by a splitter, and only the data signal is transmitted to the ADSL modem. Next, Figure 14 shows a schematic diagram of a configuration of the modem.

Herein, a wideband transmission transformer embedded in the ADSL modem in Figure 14 is described.

Figure 14 Configuration diagram of the ADSL modem



Technical problems in the ADSL system are that if the transmission distance is increased in a transmission path, attenuation of signals is heightened due to an influence of line resistance or capacitance between lines. The equation (6) shows insertion loss (the amount of attenuation) L(dB) in the telephone line as a function of transmission distance d and the frequency f[*5,6)] (where k_1 and k_2 are constants).

Table 2 Kinds and transmission methods of the xDSL system

xDSL system	Data transmission speed	Transmission medium	Transmission distance
HDSL (High-bitrate Digital Subscriber Line)	Increase : 1.5M to 2Mbps Decrease : 1.5M to 2Mbps	2 pair-metal cable	3.6km
SDSL (Symmetric Digital Subscriber Line)	Increase : 64k to 2Mbps Decrease : 64k to 2Mbps	1 pair-metal cable	2.4km to 6.9km
ADSL (Asymmetric Digital Subscriber Line)	Increase : 16k to 640Mbps Decrease : 1.5k to 12Mbps	1 pair-metal cable	2.7km to 5.5km
VDSL (Very high-bitrate Digital Subscriber Line)	Increase : 1.5k to 2Mbps Decrease : 13k to 52Mbps	1 pair-metal cable and fiber	0.3km to 1.4km

$$L=(dB)=(20d/\ln 10)\times\sqrt{k_1f^{(1/2)}k_2f} \quad \cdots\cdots\cdots\cdots \ (6)$$

It can be seen from equation (6) that the attenuation is greater as the frequency is heightened. The notable attenuation of the high frequency signal means that it is difficult to make the transmission faster. Likewise, it is essential to high-speed communication for transformers positioned at both ends of the transmission path to accurately transmit a signal from the primary side to the secondary side without distortion in the waveform of the signal.

6-2. Important characteristics of the wideband transmission transformer for The ADSL modem

The specifications for the wideband transmission transformer in an ADSL modem are diversified by design methods. However, in general, the specifications include the following items.

THD:
Inductance:
Insertion loss:
Return loss:
Leakage inductance:
Withstanding voltage: AC.1500Vrms 1min

6-3. Transmission characteristics of the transformer and magnetic core material characteristics

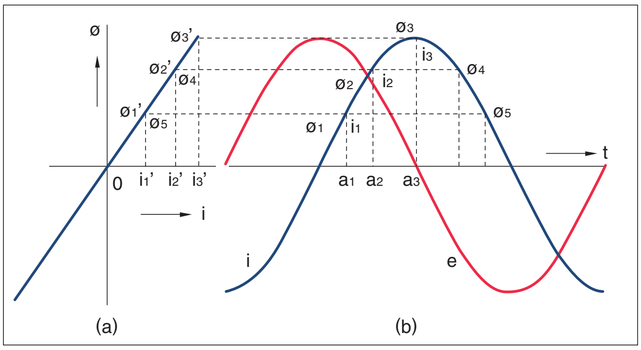
The ADSL has progressed by maximally suppressing attenuation on the transmission path or deterioration in signal waveforms due to noise, but since attenuation or distortion increase due to the transformer, both of them amount to nothing. It is especially important to minimize the distortion of the signal waveform in transmissions using a broadband transmission method with a transformer for an ADSL modem. When the signal is greatly distorted due to the transformer, the transmission cannot be made faster due to loss of data. As an index indicating the distortion of a waveform in the transformer, there is a characteristic called a total harmonic distortion (THD).

6-4. On the Total Harmonic Distortion(THD)

Mechanisms regarding generation of distortion of the signal waveform

It is ideal that when coils are wound on the magnetic core to perform a signal transmission, an excitation current showing a waveform of exactly the same shape as a current in the secondary winding is generated through excitation of the primary winding. Figures 15(a) and (b) show a current and a magnetic flux density when coils are wound on an ideal magnetic core for excitation, and an excitation voltage and an excitation current waveform at that time. In this case, the distortion is 0.

Figure 15 Current waveforms in the ideal magnetic core (transformer)



Actually, however, even the softest magnetic materials have saturation of the magnetic flux density or an area (hysteresis loss) as the amount of loss in the hysteresis loop in the B-H curve. Therefore, a signal transmitted from the primary side is considerably distorted in the waveform at the secondary side. The mechanism of the distortion is as follows.

Distortion due to magnetic saturation

Figure 16(c) shows a saturation curve when coils are wound on a magnetic core for excitation. Also, Figure 16(d) shows in parallel thereto a sinusoidal curve indicating variation in the magnetic flux at that time.

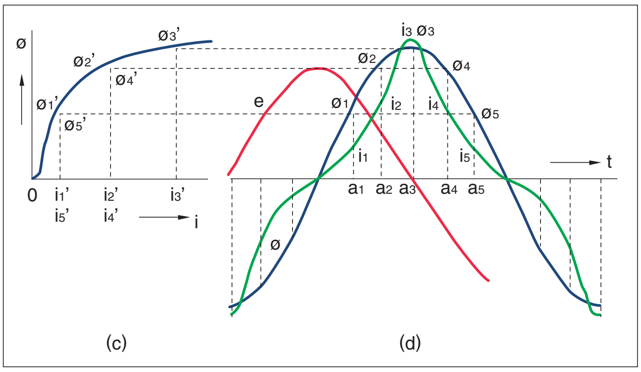
The transverse axis of the waveform of the magnetic flux in Figure 16(d) is divided into points a_1, a_2, a_3, ..., and the respective values $ø_1$, $ø_2$, $ø_3$ ... of the magnetic flux for them are obtained.

Next, on the saturation curve in Figure 16(c), a point $ø'_1$, corresponding to the point $ø_1$ is obtained, and a vertical line is drawn from the point $ø'_1$ to obtain an excitation current i'_1 for the $ø_1$.

Also, a point i_1 is decided on $a_1ø_1$ in Figure 16(d) by taking a_1i_1 equal to i'_1 (= $0i'_1$) from a_1. Likewise, a point i_2 is determined on the $a_2ø_2$ by taking a_2i_2 equal to an excitation current i'_2 (= $0i'_2$) for i_2. In this way, points i_3, i_4, ... are obtained and the points i_1, i_2, i_3, ... are connected to each other to obtain the excitation current waveform i. If the point a_3 is designated as the point for the maximum value $ø_3$ of the sinusoidal curve, the excitation current also becomes the maximum value i_3, and the waveform of the excitation current i is symmetric with respect to the point i_3. The excitation voltage E is preceding the current by $\pi/2$.

As described above, the maximum value i_3 of the excitation current increases for the same maximum magnetic flux $ø_3$ as the degree of the saturation of the magnetic core becomes larger, and this sharpens the waveform. In this way, the distortion is generated by the magnetic saturation.

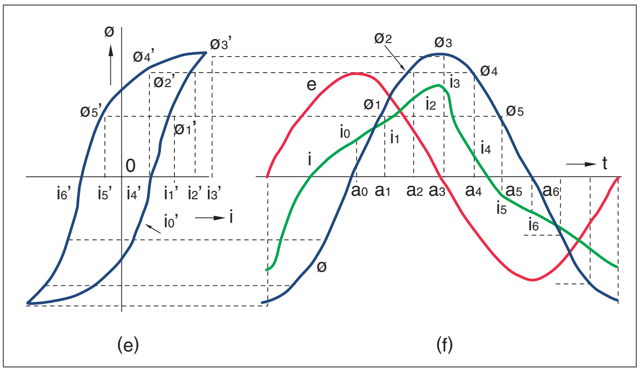
Figure 16 Distortion in the current waveform due to the magnetic saturation



Distortion due to the hysteresis loss

All of the magnetic cores have hysteresis loss in the B-H loop. The example is shown in Figure 17(e).

Figure 17 Distortion in the current waveform due to the hysteresis loss



In a case where the excitation current becomes smaller than this, the magnetic flux for the same excitation current value is increased as compared with a case where the excitation current becomes larger. In other words, two excitation currents with different magnitudes are generated for a magnetic flux with the same magnitude. In the sinusoidal magnetic flux curve in Figure 17(f), the excitation current i_2 ($= a_2i_2 = 0i'_2$) for the increasing magnetic flux $ø_2$ becomes larger than the excitation current i_4 ($= a_4i_4 = 0i'_4$) for the decreasing magnetic flux $ø_4$ with same magnitude.

Accordingly, in order that magnetic flux varies in the sinusoidal waveform, the waveform of the excitation current is twisted asymmetrically with respect to the maximum value as shown in the current waveform i in Figure 17(f). The maximum value i_3 ($= a_3i_3 = 0i'_3$) of the excitation current is generated corresponding to the maximum value $ø_3$ of the magnetic flux. Since the excitation current i_0 ($= a_0i_0 = 0i'_0$) is positive at the point a_0 where the magnetic flux is reduced to 0 and the excitation current i_6 ($= a_6i_6 = 0i'_6$) is negative at the point a_6 where the magnetic flux is reduced to 0, the waveform of the excitation current leans to the left, that is, in the direction where the phase progresses.

As described above, the waveform is distorted due to the hysteresis loss of the magnetic core[1]. The eddy current loss is generated as the frequency is heightened in the B-H loop in the actual AC, and when the frequency is heightened at the same magnetic flux density, the coercive force Hc becomes larger to further increase the loss total (hysteresis loss + eddy current loss), and this tends to increase the THD.

Definition of Total Harmonic Distortion (THD)

The distortion (in the sinusoidal wave not including the DC component) generated by the two mechanisms described above actually appears in frequencies of odd harmonics (n-order harmonics distortion), and the ratio of a sum total of the amount of distortion ($V_{(2j+1)}$) to the fundamental harmonic (V_1) is represented as dB, which is referred to as THD (Total Harmonic Distortion) and is expressed by equation (7).

$$\mathrm{THD} = 20 \log \Sigma \sqrt{V_{(2j+1)}{}^2 / V_1{}^2} \quad \cdots\cdots\cdots \ (7)$$

6-5. On the magnetic core material of wideband transmission transformer for ADSL

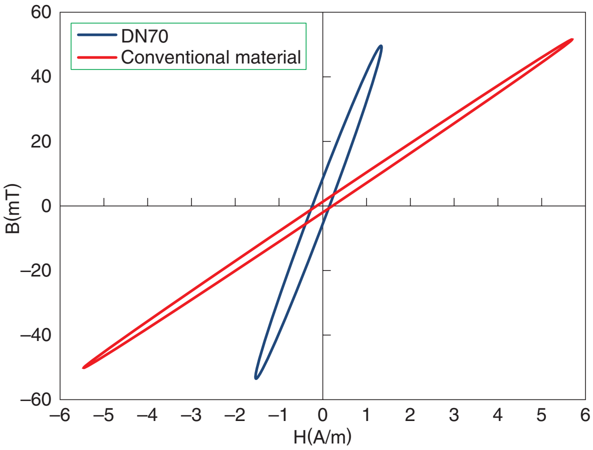
If a transformer with a low distortion is to be fabricated, the magnetic core material thereof is very important, as has been described above. In order to reduce the THD, it is necessary to use a magnetic core with as a loss low as possible. Of the soft magnetic materials, MnZn ferrite is used for magnetic core since the crystal magnetic anisotropy and the magnetostriction constant are small and loss in high frequencies is low; however, recently, a material dedicated to ADSL modem transformers has been developed, and thus it is possible to design a transformer with a much lower THD.

Figure 18 shows the B-H loop when the magnetic flux density of the THD material (DN70 material) for the ADSL and the conventional transmission transformer material is 50mT. It can be seen from the figure that the hysteresis is decreased in DN70. When a transformer is actually designed using this material, DN70 can reduce the

TDK

THD by about –5dB as compared with the conventional material in the low frequency range.

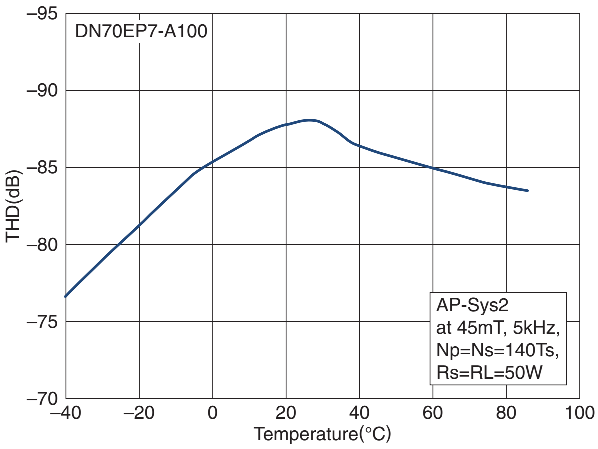
Figure 18 B-H loop of magnetic core for ADSL



Temperature characteristic and frequency characteristic of the THD

The THD has a temperature characteristic and a frequency characteristic depending its magnetic core characteristic. The temperature characteristic of the THD in the transformer using DN70 material is shown in Figure 19.

Figure 19 Temperature characteristic of the THD



The operational temperature in the ADSL modem is mainly based on indoor environments. For this reason, it is appropriate to select a magnetic core (transformer) based mainly on the THD and inductance characteristic in the vicinity of the room temperature. However, in a case of using a modem in a special environment (temperature environment), it is necessary to consider characteristics in that temperature range.

Figure 20 shows the frequency characteristic of the THD in the transformer. The frequency characteristic is evaluated such that a voltage e of the transmission signal becomes constant as shown in equation (8).

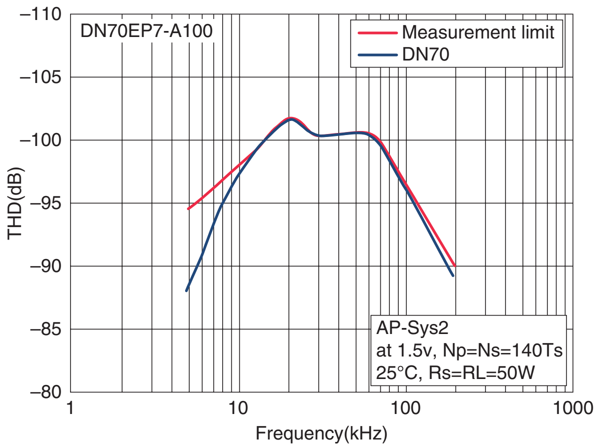
$$e=4.44\times f\times N\times Ae\times B \qquad \cdots\cdots\cdots\cdots (8)$$

f: frequency (Hz)
N: turns ratio
Ae: effective cross-sectional area (m^2)
B: magnetic flux density (T)

This is because the ADSL modem is designed such that the voltage in equation (8) becomes constant. Therefore, the measurement frequency f is reversely proportional to the magnetic flux B, and thus if the measurement frequency f is heightened, the magnetic flux density B is decreased. It can be seen from Figure 20 that the THD is reduced as the frequency is heightened, but this is because the measurement frequency f is heightened, the magnetic flux density B having a great influence on the increase in the hysteresis loss is reduced, and thereby the hysteresis loss is reduced. The THD tends to be reduced to the minimum and then be increased accompanied by an increase in the frequency, but this is likely to exceed the measurement limits of a measurement system.

Therefore, it is important to design the transformer in consideration of the THD in the low frequency range in which it is the most difficult to satisfy the driving conditions. There are frequent cases where even a specification of the typical transformer for the ADSL modem requires a THD standard in a high magnetic flux density of 30 to 50mT at a low frequency of f=5kHz.

Figure 20 Frequency characteristic of THD



Inductance

In the meantime, the transformer for an ADSL modem has a filtering function as well as signal transmission. Since the filtering function is performed by the resonance of the inductance of the transformer and capacitance in a circuit, there is a case where a tolerance lower than the typical inductance tolerance of a transformer is needed, and thus a settable range is to be checked.

In addition, a typical specification of the transformer includes standards such as impedance, insertion loss, withstanding voltage, and the like, but it is necessary to select a magnetic core (transformer) after fully considering the actual driving conditions and operational environment temperature.

6-6. Core shape and winding method

It is said that if the constants CDF and SDF expressed by the following equations (9) to (11) become smaller in relation to the core shape of the transformer for the ADSL, the THD is reduced[2).

$$CDF \fallingdotseq (L_e/A_e^2) \times (L_N^{(3/2)}/A_N^{(3/2)}) \quad \cdots\cdots\cdots\cdots (9)$$

$$SDF \fallingdotseq \sqrt{L_e^5/L_N^3} \times (A_e/A_N^3))^{(1/2)} \quad \cdots\cdots\cdots\cdots (10)$$

$$CDF \fallingdotseq SDF \times (1/V_e^{(3/2)}) \quad \cdots\cdots\cdots\cdots (11)$$

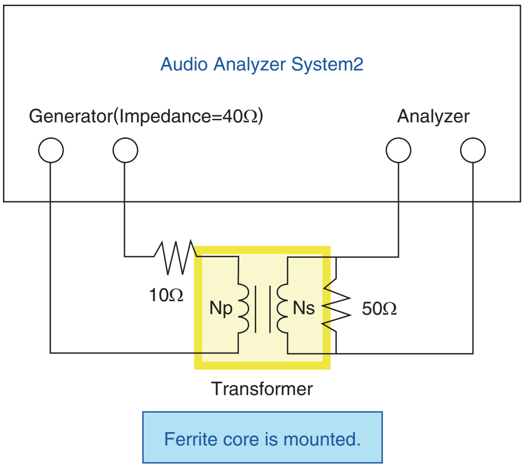
CDF: Core Distortion Coefficient
SDF: Shape Distortion Coefficient
L_e: magnetic pass length on IEC60205
A_e: cross-sectional area on IEC60205
L_N: Coil former's means turn length
A_N: Coil former's means cross section

It can be seen from the equation (11) that as the core volume increases, the THD decreases. It is thought that since the magnetic flux density generated in the magnetic core decreases due to the increase in the core volume, the loss is reduced, with respect to the same setting voltage. It is known that the SDF is reduced by a shape called an EP shape as a result of actually calculating the SDF regarding various shapes by using nearly the same sizes in the outer appearance’s dimensions. Actually, cores are used in ADSL, and most of the cores have the EP shape (EP7, EP13) or a similar shape. The winding structure generally employs a sandwich winding in order to reduce leakage inductance.

6-7. THD evaluation method

It has been described that the THD is important in a transformer for an ADSL modem, and the evaluation method thereof is made as follows. The device used to perform the measurement is an audio analyzer, and, as an example, a transformer is installed on the circuit as shown in Figure 21, thereby measuring the THD.

Figure 21 THD evaluation system



Since the measurement is performed in a very delicate manner, generally, it is necessary to perform the evaluation under an environment where external noise or stress to the transformer are maximally suppressed.

In addition, when the THD measurement is performed at a constant voltage, there is a case where the THD becomes far lower on the high frequency side than the characteristic of the magnetic core described above and thus exceeds measurement limits (refer to Figure 20). For this reason, it is also necessary that the primary side and the secondary side are initially short-circuited to understand the measurement limits of the measurement system and thereafter measurement is performed.

TERMS

- Broadband transmission:
  A method in which encoded digital data (signal) transmitted from a PC or the like is carried on an analog wave (modulation) for transmission to another party

- Baseband transmission:
  A method in which encoded digital data (signal) transmitted from a PC or the like is not modulated and transmitted to another party as the digital data

- Eddy current loss:
  An amount of the loss generated by an eddy current which occurs in a magnetic body due to electromagnetic induction (magnetic flux is generated in a direction hindering magnetic flux from an external magnetic field).
  (In the case of the MnZn ferrite, it increases in proportion to the square of the frequency.)

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• Please note that the articles from the December, 2003 Edition of the Transistor Technology contained in this chapter have been edited by our company.