

# Determination of B-H Curve of Core Material of Transformer

## 1 Aim

To determine of B-H curve of core material of transformer

## 2 Theory

The rms voltage induced in a transformer is given by

$$E = 4.44\phi_m f N \quad (1)$$

where,  $\phi_m$  is maximum value of the flux in the core,  $f$  is operating frequency and  $N$  is number of turns in the coil. This flux in the coil is given by

$$\phi_m = B_m A_c \quad (2)$$

where,  $B_m$  is the maximum flux density in core and  $A_c$  is the cross-sectional area of the core. So we have

$$E = 4.44B_m A_c f N \quad (3)$$

The value of induced voltage  $E$  is thus dependent upon  $B_m$  which can be setup in the core.

### 2.1 DC Magnetization Curve

We know from Biot-Savart's law that a current carrying conductor produces magnetic field. "Magnetic field strength"  $\mathbf{H}$  is proportional to the current which produces the field. From Ampere's Circuital law, it can be proved that  $\mathbf{H}$  is proportional to current  $I$ . If a current carrying coil produces magnetic flux which traverses an average length of  $l$  in complete flux path, then

$$Hl = NI \quad (4)$$

In a magnetic circuit, this field is represented by *magnetomotive force*. It is analogous to the *electromotive force* in electrical circuit.

This field is responsible to "set up" certain flux, which in turn gives rise to certain flux density  $\mathbf{B}$ . Note that, here  $\mathbf{H}$  is cause and  $\mathbf{B}$  is its effect. The amount of flux which *can be* setup in a material is determined by an inherent property of the material, called as *permeability*, denoted by  $\mu$ .

$$\mathbf{B} = \mu\mathbf{H} \quad (5)$$

More details on analysis of magnetic circuits can be found in chapter 2 in [1].

Let us consider materials used in the laminations of transformers. They are called *ferromagnetic materials*. A piece of ferromagnetic material is composed of several "domains". In each domain, magnetic moments of all atoms are aligned in one direction. In general, the domains are randomly oriented. When external magnetic field  $\mathbf{H}$  is applied to a material, all the domains align in a particular direction, setting up "net flux" in the material. Due to domain alignment  $B$  (i.e. the magnitude of  $\mathbf{B}$ ) increases. However, after a certain value of  $B$ , the slope of  $B - H$  curve starts reducing as shown in Fig. 1;  $O - S_1$  represents the linear region and  $S_1 - S_2$  represents the "saturation region". Note that

$$\left. \frac{dB}{dH} \right|_{O-S_1} > \left. \frac{dB}{dH} \right|_{S_1-S_2} \quad (6)$$

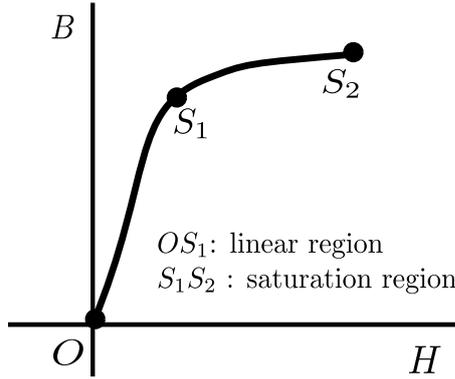


Figure 1: DC magnetization curve

In other words, for same increment in  $B$ , one has to apply more excitation in saturation region than in linear region. This is called as *DC Magnetization Curve* as both  $B$  and  $H$  have same sign. It is interesting to see what happens when the external magnetic “excitation” is removed or reduced to zero. Discussion in the following section, applies to this case and also the case of AC circuits in general.

## 2.2 Hysteresis Loop

Removing external magnetic field is equivalent to reducing  $H$  from  $H_{max}$  to 0. Due to this, the domains which were aligned in the direction of external field, “become free” of the external magnetic force. However, now they do not attain completely random orientation as they had at  $(B = 0, H = 0)$ . Some domains maintain the direction of external magnetic field. This results in remanent magnetic flux density  $B_r$ . In short, while  $H$  traverses the trajectory  $0 - H_{max} - 0$ ; magnetic flux density  $B$  traverses  $0 - B_{max} - B_r$ , as shown in Fig. 2. In order to reduce flux density to zero we have to apply external magnetic field in the opposite direction or on the negative  $H$ -axis.

If external field is increased in the *opposite* direction, the behaviour of magnetic material is seen analogous to that of the positive quadrant. Complete  $B - H$  curve for is shown in Fig. 2. It is also called as “Hysteresis loop<sup>1</sup>” traced by the flux density in the material.

## 2.3 Determination of $B - H$ curve of a material

We cannot “measure”  $B$  and  $H$  directly. Further if we have transformer, we only have terminal measurements at our disposal. Hence, it is required to “process” the signals to get values of  $B$  and  $H$ .

From Faraday’s law,

$$V = N \frac{d\phi}{dt} \quad (7)$$

Also, from equation 2,  $B$  is directly proportional to flux  $\phi$ . A signal proportional to  $B$  can be obtained by integrating the voltage signal. The voltage can be integrated approximately by using an RC circuit. Care should be taken in the choice of  $R$  and  $C$  values. The transfer function of the circuit is given by

$$\frac{V_c(s)}{V_{in}(s)} = G(s) = \frac{1}{1 + s\tau}$$

The time constant  $\tau = RC$  should be chosen such that, in frequency domain  $(1 + j\omega\tau) \approx j\omega\tau$

<sup>1</sup>The term *Hysteresis* is used for a system which has memory or causal systems. In this case, the material *remembers* last value of applied field in terms of  $B$ .

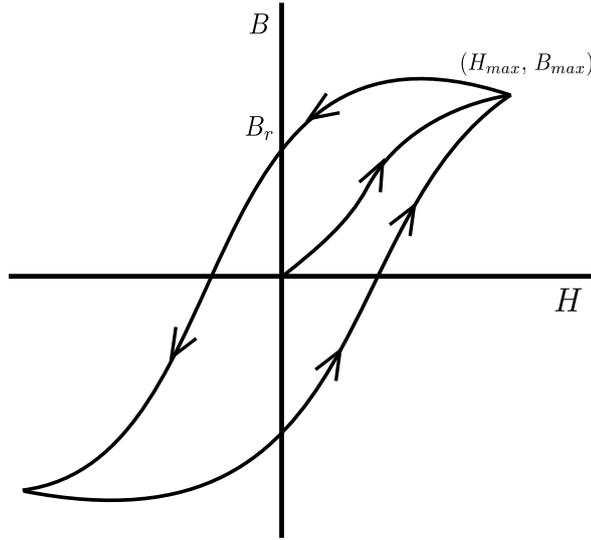


Figure 2:  $B - H$  curve or Hysteresis loop

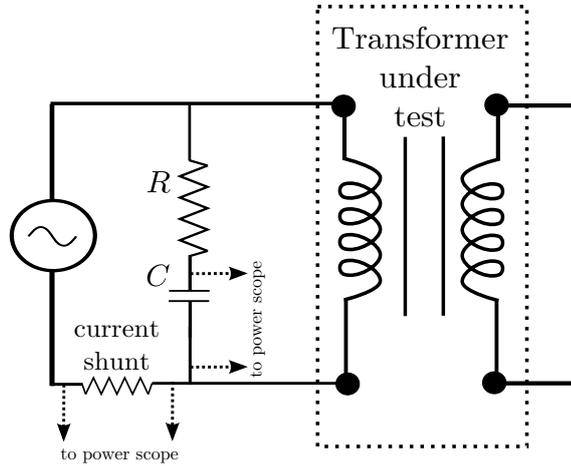


Figure 3: Connection diagram of circuit to trace  $B - H$  curve measurement

Equation 4 tells that  $H$  is proportional to current. The two signals can be given to two channels of a digital storage oscilloscope.  $B - H$  curve of the material can be seen by plotting using *Lissajous*<sup>2</sup> plot settings of the oscilloscope.

## 2.4 Epstein Meter

Another way to visualize  $B - H$  curve of the material is by using Epstein Meter. This meter is used to visualize the  $B - H$  curve of a material which is available in form laminations. Laminations of the available material can be inserted in the apparatus and the  $B - H$  curve can be seen on the oscilloscope. The strips are inserted in the meter. The instrument is constructed such that the inserted strips form core of a transformer. No load losses in the transformer are calculated to plot B-H curve of the material. For more details please refer [2], [3].

<sup>2</sup>In Lissajous plot the signals from two channels are plotted against each other. Otherwise, each signal is plotted against time.

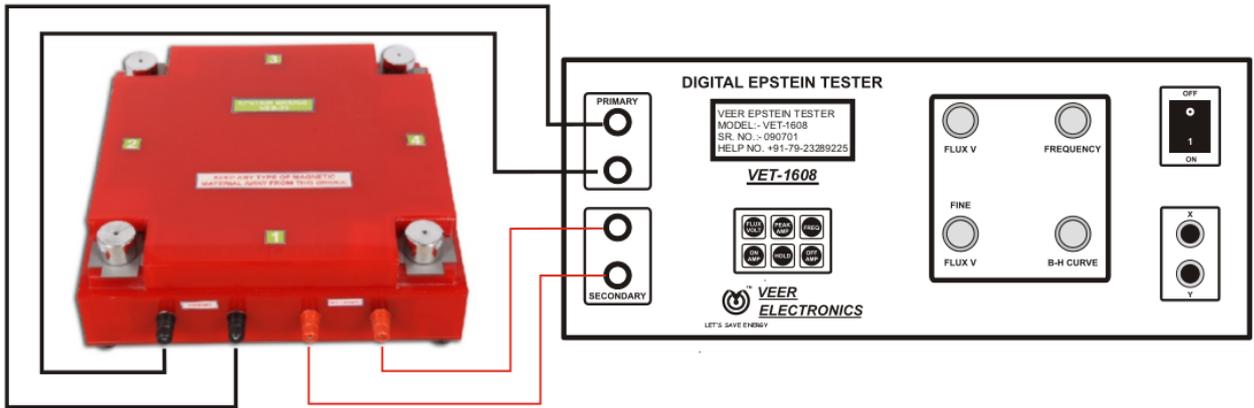


Figure 4: Epstein Meter (image courtesy: Epstein meter manual by Veer Electronics [4])

### 3 Procedure

1. Connect the apparatus as shown in the Fig. 3.
2. Connect the voltage and current signals to the oscilloscope.
3. Use “Lissajous” figure settings to see the  $B - H$  curve on digital storage oscilloscope.
4. Record the oscilloscope data in digital form.

### 4 Report

1. Plot data of  $B - H$  curve using MATLAB/gnuplot or any other suitable package.
2. Can you obtain value of permeability  $\mu$  with this data? If yes, derive formula for the same.

### 5 Post-lab Questions

1. Why is a ferromagnetic core required in transformers?
2. Permanent magnets exhibit a different type of  $B - H$  curve. How does it differ from  $B - H$  curve for ferromagnetic materials?
3. The material used for a transformer core is a steel variant with  $\mu_r = 5000$ . The average length of the magnetic path in the core is 50 mm. The number of turns in primary is 500. The cross sectional area of the core is 600 mm<sup>2</sup>. The applied voltage is 230 V, 250 Hz. The secondary coil is open circuited. The  $B - H$  curve of the material is as shown in Fig. 1. Is the transformer operating in saturation region? Why?
4. Note that flux density is inversely proportional to frequency (see equations 1 and 2). How would the design of a transformer be affected by the frequency? (Hint: What will be effect on cross sectional area of a core)
5. Consider two power supplies (adapters) shown in Figs. 5 and 6. Which has lower weight and size? Why?

### References

- [1] A. E. Fitzgerald, C. Kingslay, and S. Umans, *Electric Machinery*. New Delhi: Tata McGraw Hill, 2002.

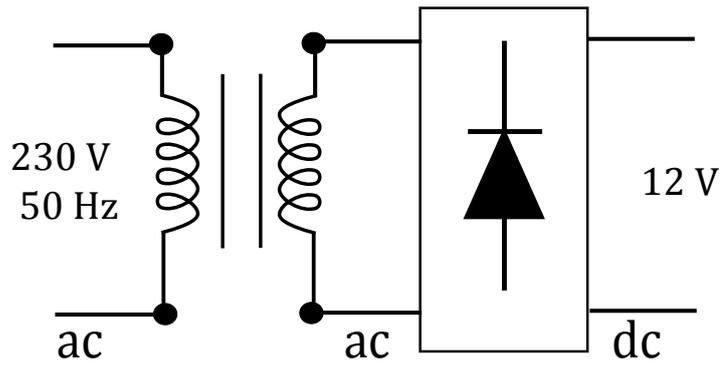


Figure 5: Adapter 1

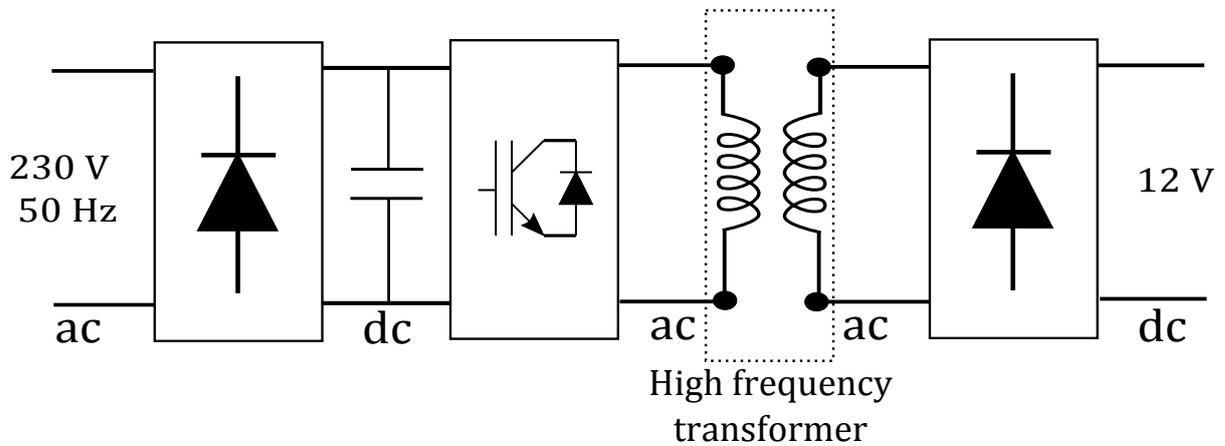


Figure 6: Adapter 2

- [2] *Methods for determining the magnetic properties of magnetic steel sheet and strip with 25 cm Epstein frame*, European Commission Std. 118-87, 1988. [Online]. Available: <http://bookshop.europa.eu/en/euronorm-118-87-pbCB4887670/>
- [3] *Standard Test Method for Alternating-Current Magnetic Properties of Materials at Power Frequencies Using Wattmeter-Ammeter-Voltmeter Method and 25-cm Epstein Test Frame*, ASTM International Std. A343/A343M.
- [4] *Operation Manual, Model VET-1608 Digital Epstein Tester*, Veer Electronics.