1.6 HYSTERESIS AND EDDY CURRENT LOSSES

The area enclosed by the loop is a power loss known as the hysteresis loss, and can be calculated by

$$P_{hyst} = \oint \mathbf{H} \bullet d\mathbf{B} \quad (\text{W/m}^3\text{/cycle}) \text{ or } (\text{J/m}^3)$$

For magnetic materials commonly used in the construction of electric machines an approximate relation is

$$P_{hyst} = C_h f B_p^n \quad (1.5 < n < 2.5) \quad (\text{W/kg})$$

Where

C_h = constant determined by the nature of the ferromagnetic material,

f = frequency of excitation, and B_p is the peak value of the flux density.

When the excitation field varies quickly, by the Faraday's law, an electromotive fore (*emf*) and hence a current will be induced in the conductor linking the field as shown in figure 1.9 . Since most ferromagnetic materials are also conductors, eddy currents will be induced as the excitation field varies, and hence a power loss known as eddy current loss will be caused by the induced eddy currents. The resultant *B-H* or □-*i* loop will be fatter due to the effect of eddy currents, as illustrated in the diagram below. Under a sinusoidal magnetic excitation, the average eddy current loss in a magnetic core can be expressed by

$$P_{eddy} = C_e \left(f B_p \right)^2 \qquad (\text{W/kg})$$

where C_e is a constant determined by the nature of the ferromagnetic material and the dimensions of the core.

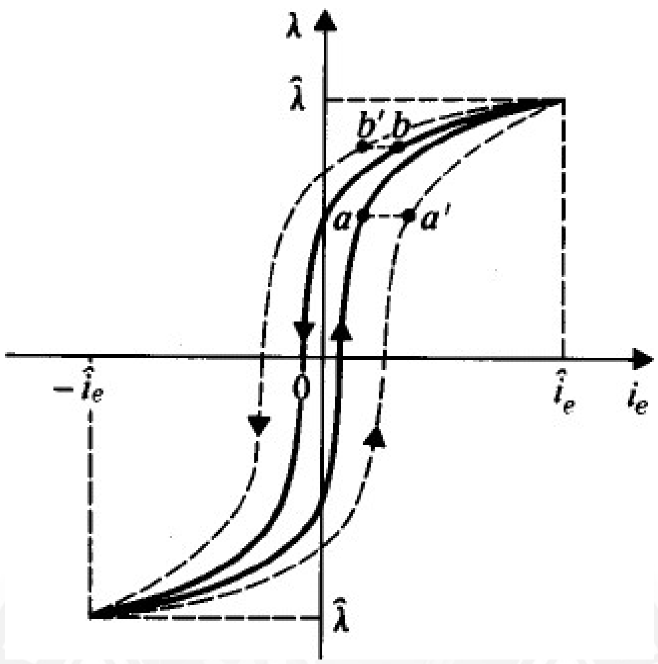

Figure 1.6.1 Hysteresis Loop

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman*, Page: 81]*

Fig 1.6.1 Relationship between flux linkage and excitation current when eddy current is included (dashed line loop), where the solid line loop is the pure hysteresis obtained by dc excitation.

Since the eddy current loss is caused by the induced eddy currents in a magnetic core., an effective way to reduce the eddy current loss is to increase the resistivity of the material. This can be achieved by adding Si in steel. However, too much silicon would make the steel brittle. Commonly used electrical steels contain 3% silicon.Another effective way to reduce the eddy current loss is to use laminations of electrical steels. These electrical steel sheets are coated with electric insulation, which breaks the eddy current path, as illustrated in figure 1.6.2 .

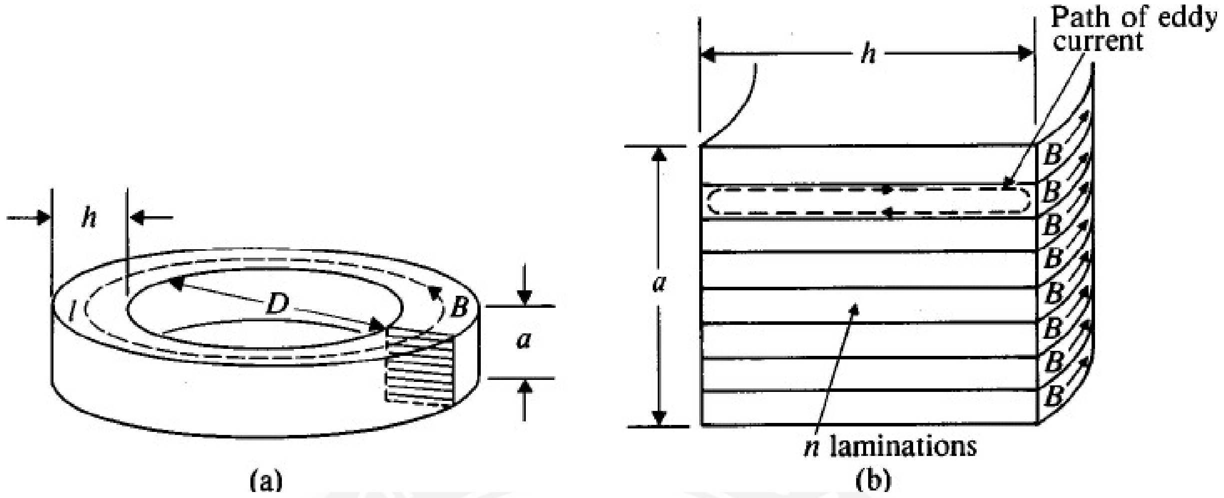

Figure 1.6.2 Eddy currents in a laminated toroidal core

[Source: "“Electric Machinery Fundamentals" by Stephen J. Chapman*, Page: 86]*

The above formulation for eddy current loss is obtained under the assumption of global eddy current as illustrated schematically in figure1.6.2 (a) of the following diagram. This is incorrect for materials with magnetic domains. When the excitation field varies, the domain walls move accordingly and local eddy currents are induced by the fluctuation of the local flux density caused by the domain wall motion as illustrated in figure1.6.2 (b) of the diagram below. The total eddy current caused by the local eddy currents is in general higher than that predicted by the formulation under the global eddy current assumption.

The difference is known as the excess loss. Since it is very difficult to calculate the total average eddy current loss analytically, by statistical analysis, it was postulated that for most soft magnetic materials under a sinusoidal magnetic field excitation, the excess loss can be predicted by

$$P_{ex} = C_{ex}\left(fB_p\right)^{3/2} \qquad \text{(W/kg)}$$

where *C*ex is a constant determined by the nature of the ferromagnetic material. Therefore, the total core loss can be calculated by

$$P_{core} = P_{hyst} + P_{eddy} + P_{ex}$$