1.3 MAGNETIC CIRCUIT CALCULATIONS

- The path of the magnetic flux is called a magnetic circuit.
- A magnetic circuit is analogous to an electric circuit. A review of laws of magnetic circuits is given below.

In an electric circuit Ohm’s law expresses a relationship between current, emf and resistance. While in a magnetic circuit, a similar relation exists relating flux, mmf and reluctance.

This relation is:

$$\text{flux}=\frac{\text{mmf}}{\text{relutane}}$$

$$\Phi=\frac{AT}{S}$$

$$\Phi = AT \times S$$

The reluctance of the magnetic material can be esusing the following equation.

$$\text{Reluctance}=\frac{\text{Length}}{\text{area x permeability}}$$

$$\boxed{S=\frac{l}{A\mu}}$$

Table 1 Differences between electric and magnetic circuits

ELECTRIC CIRCUIT	MAGNETIC CIRCUIT
Current actually flows in the electric circuit.	Flux does not flow, but it is only assumed to flow.
When current flows, the energy is spend continuously.	Energy is needed only to create the flux but not to maintain it.
Resistance of the electric circuit is independent of current strength.	Reluctance of the magnetic circuit depends on total flux or flux density in the material.

Magnetic Curve (B-H Curve)

In magnetic materials, the magnetizing force required to establish a given flux density depends on the saturation of the material. If the material is not saturated, then a small increase in magnetizing force will result in a proportional increase in flux density. But when the material is saturated, a large increase in magnetizing force will result in a small increase in flux density. Therefore, the permeability of the magnetic material is not constant

In a non-magnetic material like air, copper, etc. there is no such phenomena of saturation. Hence the permeability of non-magnetic material is constant and the relation between B and H is linear. Therefore, the B-H curve will be straight line passing through origin.

In magnetic materials, the relation between the flux density B and the magnetizing force H is nonlinear. Hence, it is difficult to express the relation in terms of mathematical equation. Therefore, to calculate mmf per meter of flux path for a given flux density the B-H curve is employed.

The manufacturers of stamping or laminations for transformer, induction motor, ac machines etc will supply B-H curve. These curves are used to estimate magnetizing force and core loss for a given flux density or for a required flux density in any part of the machine.

By using digital computers, the analytic relations between B and H prove more convenient. Two of the most used mathematical relationships are given below.

$$B = \frac{aH}{1+bH} \qquad \textbf{(1)}$$

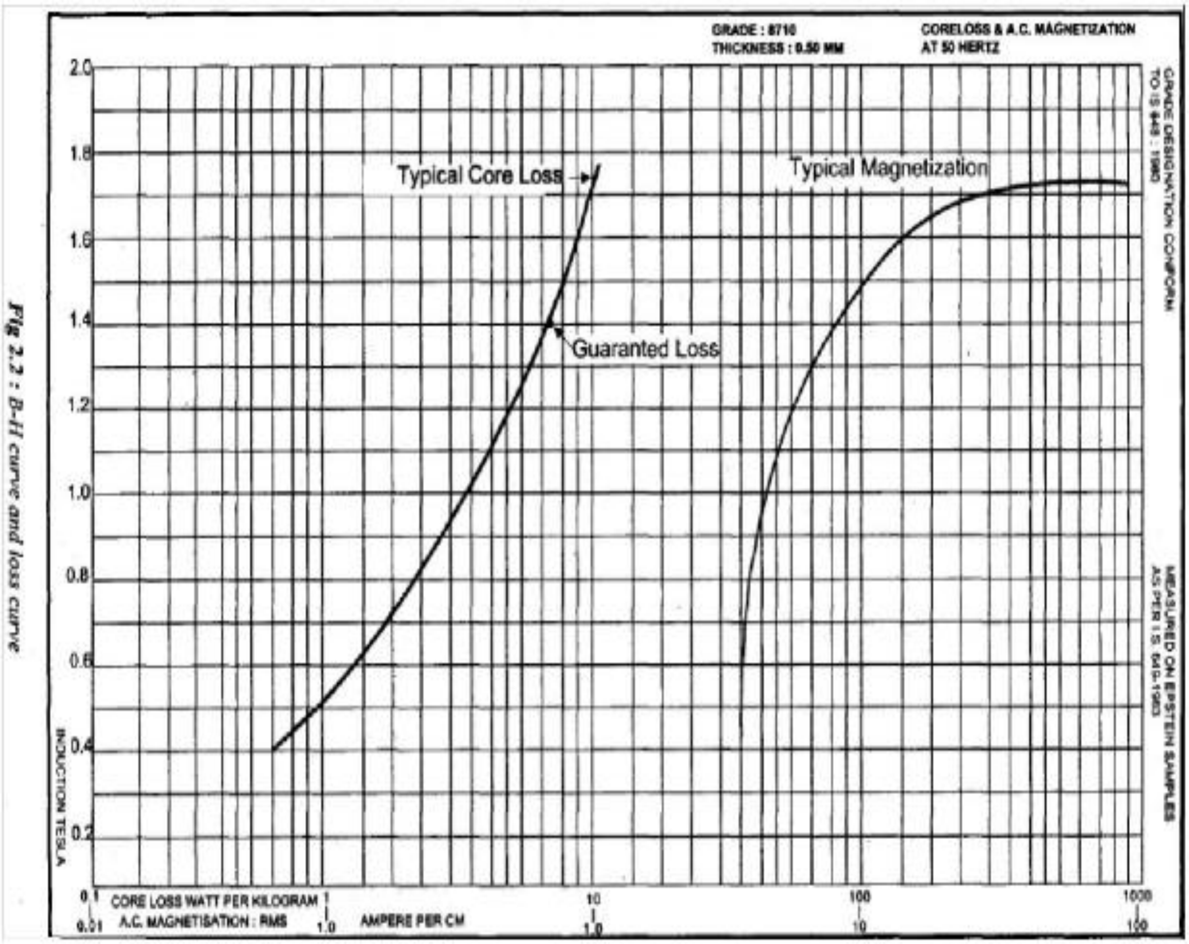


Figure 1.3.1 B-H Curve

[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-3.3]

Magnetic Leakage

For magnetic circuit calculations, a term 'leakage co-efficient' is introduced in order to take into account the leakage flux. The value of this leakage co-efficient is defined as

$$\text{Leakage co-efficient, C} = \frac{\text{Useful Flux+Leakage Flux}}{\text{Useful Flux}}$$

Types of Leakage Flux

The armature leakage fluxes affect most of the performance of rotating machines Hence the different types of armature leakage fluxes are discussed in this section. The different types of armature leakage fluxes are:

- Slot leakage flux
- Tooth top leakage flux
- Zigzag leakage flux
- Overhang leakage flux
- Harmonic or differential leakage flux
- Skew leakage flux
- Peripheral leakage flux

Slot leakage flux

The fluxes that cross the slot from one tooth to the next and returning through iron are called slot leakage flux. They link the conductors below them, as shown in fig.

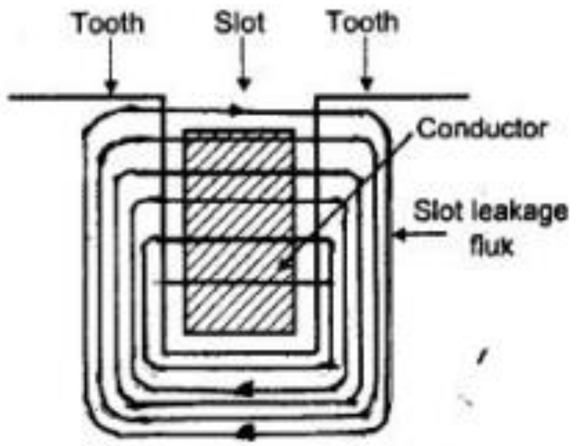


Fig. 3. Slot leakage flux

[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-3.3]

Tooth top leakage flux

The flux flowing from top of the one tooth to the top of another tooth as shown in fig. 4 is called tooth top leakage flux. This leakage flux is considered only in machines having large air-gap length like DC machines and synchronous machines. Since in induction machines the air-gap length is very small the tooth top leakage flux is negligible.

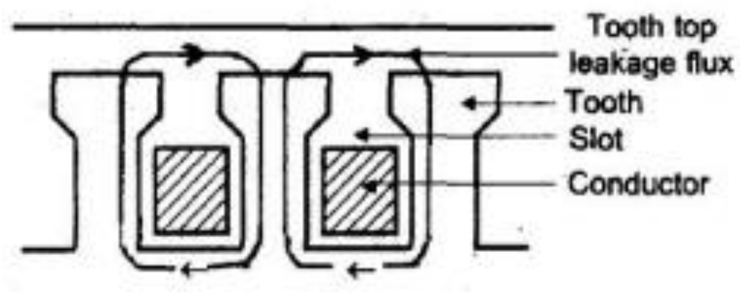


Fig. 4 Tooth top leakage flux

[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-3.3]

Zigzag leakage flux

The flux passing from one tooth to another in a zigzag fashion across the air-gap as shown in fig. 5 is called zigzag leakage flux. The magnitude of this flux depends on the length of air-gap and the relative positions of the tips of rotor a stator tooth.

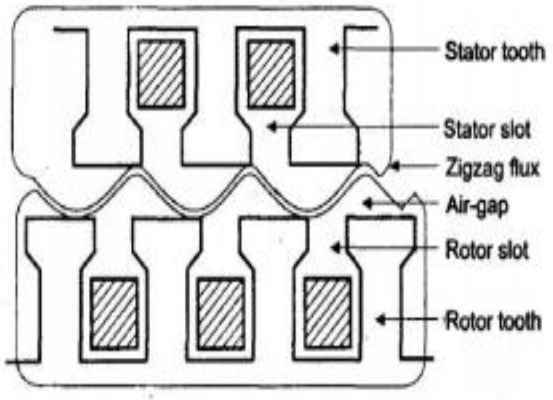


Fig. 5 Zigzag leakage flux

[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-3.3]

Overhang leakage flux

The end connections (the conductor which connects the two sides of a coil) are called overhang. The fluxes produced by the overhang portion of the armature winding are called overhang leakage flux as shown in fig 6. It depends on the arrangement of overhang and the nearby metal parts (for eg. Core stiffness and end covers)

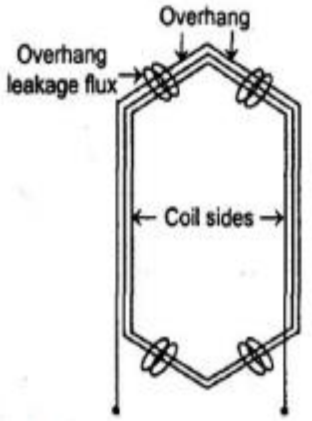


Fig. 6 Overhang leakage flux

[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-3.3]

Harmonic (or Differential or Belt) leakage flux

The harmonic leakage flux is due to dissimilar mmf distribution in the stator and rotor. Actually the difference in the harmonic contents of stator and rotor mmfs produces harmonic leakage fluxes. In squirrel cage induction motor the rotor current is exactly balanced by stator current and so there is no harmonic leakage flux.

Skew leakage flux

A twist provided in the rotor of induction motors to eliminate harmonic torques and noise is called skewing. The skewing reduces the mutual flux and thus creating a difference between total flux and mutual flux. This difference is accounted as skew leakage flux.

Peripheral leakage flux

The fluxes flowing circumferentially round the air-gap without linking with any of the windings are called peripheral leakage flux. Usually this leakage flux is negligible in most of the machines.

RELUCTANCE OF AIR-GAP IN MACHINES WITH SMOOTH ARMATURE

Let

L = length of core

y_s = slot pitch

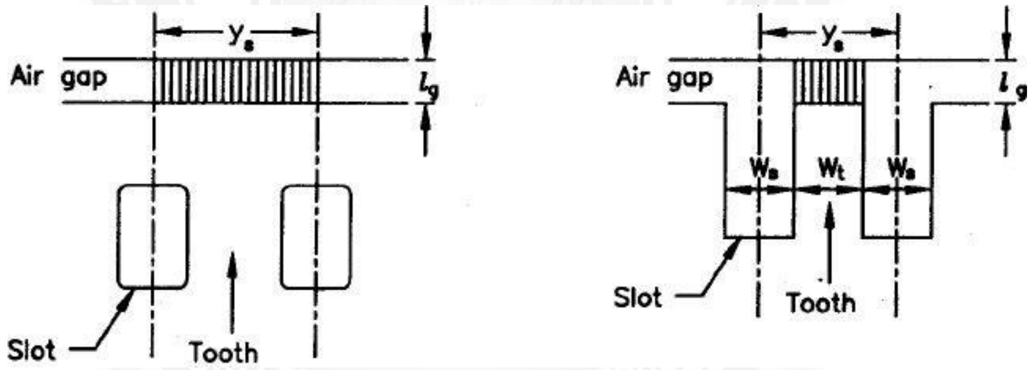
W_t = width of tooth

n_d = number of radial ducts

The iron surfaces around the air gap are not smooth and so the calculation of mmf for the air gap by ordinary methods gives wrong results. The problem is complicated by the fact that:

- One or both of the iron surfaces around the air gap may be slotted so that the flux tends to concentrate on the teeth rather than distributing itself uniformly over the air gap.
- There are radial ventilating ducts in the machine for cooling purposes which affect in a similar manner as above.
- In salient pole machines, the gap dimensions are not constant over whole of the pole pitch.

Consider the iron surfaces on the two sides of the air gap to be smooth as shown in fig. 7. The flux is



[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-3.3]

If we confine our attention to only one slot pitch, the reluctance of air gap

$$\boxed{S^g = \frac{l}{\mu_o A} \quad \frac{l_g}{\mu_o L y}}$$

RELUCTANCE OF AIR-GAP IN MACHINES WITH OPEN ARMATURE SLOTS

In armature with open and semi enclosed slots, the flux will flow through the teeth of the armature.

Hence the effective area of flux path is decreased, which results in increased reluctance of air gap.

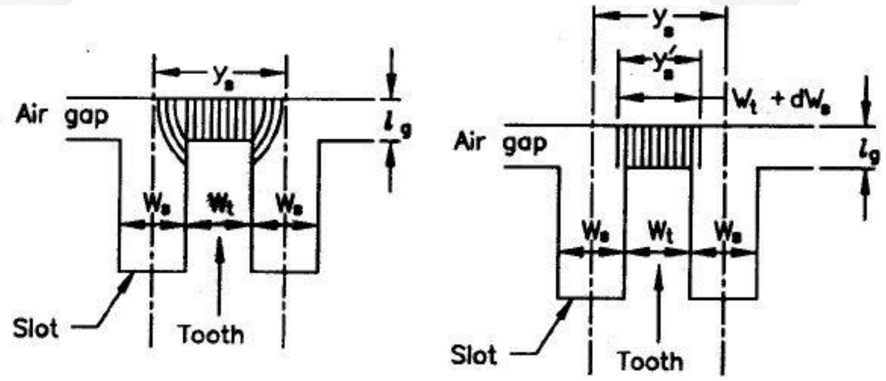
Reluctance of air-gap neglecting fringing effect

Consider the armature with open type of slots as shown in fig. 8. Here the flux is only confined to the tooth width. Hence the area of cross-section of the air gap through which the flux passes is $L(y_S - w_S)$ or Lw_t .

Reluctance of air-gap including the effect of fringing

In armature with open slots the flux would fringe around the tooth and this fringing would increase the area of cross section of flux path.

Consider the open type slot of armature shown in fig. 9. Here the fringing of flux can be accounted by increasing the area of cross-section of flux path by δw_S as shown in fig. 10.



[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-3.3]

The reluctance in this case is more than that of a air-gap in smooth armature but lesser than that of the case where the whole flux is assumed to be confined over the tooth width.

A simple method to calculate reluctance in this case is to assume that the air gap flux is uniformly distributed over the whole of slot pitch expect for a fraction of slot width as shown in fig.(b). This fraction depends on the ratio of slot width to air gap length. Thus the flux of one slot is distributed over $W_t + \delta W_S$.

Effective or contracted slot pitch

$$y' = W_t + \delta W_S$$