4.3.5 Magnetic Losses and Frequency Behavior

General Remarks

- So far we have avoided to consider the frequency behavior of the magnetization, i.e. we did not discuss what happens if the external field oscillates!
  - The experience with electrical polarization can be carried over to some magnetic behaviour, of course. In particular, the frequency response of *paramagnetic* material will be quite similar to that of electric dipole orientation, and diamagnetic materials show close parallels to the electronic polarization frequency behaviour.
  - Unfortunately, this is of (almost) no interest whatsoever. The "almost" refers to **magnetic imaging** employing **magnetic resonance imaging** (***MRI***) or *nuclear spin resonance imaging* - i.e. some kind of "*computer tomography*". However, this applies to the paramagnetic behavior of the magnetic moments of the *nuclei*, something we haven't even discussed so far.
- What is of interest, however, is what happens in a *ferromagnetic* material if you have expose it to an *changing*, i.e. oscillating magnetic field. $\boldsymbol{H = H_o \cdot \exp(i\omega t)}$
  - Nothing we discussed for dielectrics corresponds to this questions. Of course, the frequency behavior of ferroelectric materials would be comparable, but we have not discussed this topic.
  - Being wise from the case of dielectric materials, we suspect that the frequency behavior and some **magnetic energy losses** go in parallel, as indeed they do.
- In contrast to dielectric materials, we will start with looking at magnetic losses *first*.

Hystereses Losses

- If we consider a ferromagnetic material with a given hysteresis curve exposed to an oscillating magnetic field at low frequencies - so we can be sure that the internal magnetization can instantaneously follow the external field - we may consider *two* completely independent mechanisms causing losses.
  - **1.** The changing magnetic field induces currents wandering around in the material - so called ***eddy currents***. This is different from dielectrics, which we always took to be insulators: ferromagnetic materials are usually conductors.
  - **2.** The movement of domain walls needs (and disperses) some energy, these are the *intrinsic* magnetic losses or hystereses losses.
- Both effects add up; the energy lost is converted into heat. Without going into details, it is clear that the losses encountered increase with
  - **1.** The frequency $\boldsymbol{f}$ in *both* cases, because every time you change the field you incur the same losses per cycle.
  - **2.** The maximum magnetic flux $\boldsymbol{B_{max}}$ in both cases.
  - **3.** The conductivity $\sigma = 1/\rho$ for the eddy currents, and
  - **4.** The magnetic field strength $\boldsymbol{H}$ for the magnetic losses.
- More involved calculations (see the advanced module) give the following relation for the total ferromagnetic loss $\boldsymbol{P_{Fe}}$ per unit volume of the material

$$P_{Fe} \approx P_{eddy} + P_{hyst} \approx \frac{\pi \cdot d^2}{6\rho} \cdot (f \cdot B_{max})^2 + 2f \cdot H_C \cdot B_{max}$$

  - With $\boldsymbol{d}$ = thickness of the material perpendicular to the field direction, $\boldsymbol{H_C}$ = coercivity.
- It is clear what you have to do to minimize the eddy current losses:
  - Pick a ferromagnetic material with a high resistivity - *if* you can find one. That is the point where *ferri*magnetic materials come in. What you loose in terms of maximum magnetization, you may gain in reduced eddy losses, because many ferrimagnets are ceramics with a high resistivity.
  - Make $\boldsymbol{d}$ small by stacking insulated thin sheets of the (conducting) ferromagnetic material. This is, of course, what you will find in any run-of-the-mill transformer.
- We will not consider eddy current losses further, but now look at the remaining **hystereses losses** $\boldsymbol{P_{hyst}}$
  - The term $\boldsymbol{H_C \cdot B_{max}}$ is pretty much the area inside the hystereses curve. Multiply it with two times the frequency, and you have the hystereses losses in a good approximation.
  - In other words: There is nothing you can do - for a given material with its given hystereses curve.

- Your only choice is to select a material with a hystereses curve that is *just right*. That leads to several questions:
  - **1.** What kind of hystereses curve do I need for the application I have in mind?
  - **2.** What is available in terms of hystereses curves?
  - **3.** Can I change the hystereses curve of a given material in a defined way?
- The answer to these questions will occupy us in the next subchapter; here we will just finish with an extremely cursory look at the frequency behavior of ferromagnets.

Frequency Response of Ferromagnets

- As already mentioned, we only have to consider ferromagnetic materials - and that means the back-and-forth movement of domain walls in response to the changing magnetic field.
  - We do not have a direct feeling for how fast this process can happen; and we do not have any simplified equations, as in the case of dielectrics, for the forces acting on domain walls. Note that the atoms do *not* move if a domain wall moves - only the direction of the magnetic moment that they carry.
  - We know, however, from the bare fact that permanent magnets exist, or - in other words - that coercivities can be large, that it can take rather large forces to move domain walls - they might not shift easily.
  - This gives us at least a feeling: It will not be easy to move domain walls *fast* in materials with a large coercivity; and even for materials with low coercivity we must not expect that they can take large frequencies, e.g. in the optical region
  - There are materials, however, that still work in the **GHz** region.
- And that is where we stop. There simply is no general way to express the frequency dependence of domain wall movements.
  - That, however, does not mean that we cannot define a **complex magnetic permeability** $\mu = \mu' + i\mu''$ for a particular magnetic material.
  - It can be done and it has been done. There simply is no *general* formula for it and that limits its general value.

Questionaire
Multiple Choice questions to 4.3.5