Environmental Potentials

Power Quality For The Digital Age

MAGNETIC DIPOLES, HYSTERESIS AND CORE LOSES

AN ENVIRONMENTAL POTENTIALS WHITE PAPER

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Early in the study of electromagnetism, it was experimentally established that a surrounding magnetic field is always associated with a changing electric current in a conductor.

It was determined that the magnetic force field existed at right angles to the vector direction of the current. The source of the magnetic field is charge in motion, or current. This magnetic field can also be visualized as a torque force and occurs at a distance through a 'lever' arm. The force is perpendicular to the 'arm', and gives rise to circular rotation. This is further described as a *magnetic dipole moment.* Magnetic materials, from lodestones to video tapes, are magnetic because of the electrons within them. An electron has an intrinsic angular momentum called its **spin angular momentum** (or just **spin**). Associated with this spin is an intrinsic **spin magnetic dipole moment.** When it is in an atom, an electron has an additional angular momentum called its **orbital angular momentum,** and associated with that is an **orbital magnetic dipole moment.** Each electron in an atom has an orbital dipole moment and a spin magnetic dipole moment that combine vectorially. The resultant of these two vector quantities combines vectorially with similar resultants for all other electrons in the atom, and the resultant for each atom combines with those for all the other atoms in a sample of a material. If the combination of all these magnetic dipole moments produces a magnetic field, then the material is magnetic. There are three general types of magnetism: diamagnetism, paramagnetism, and ferrmagnetism.

1. Diamagnetism is exhibited by all common materials but is so feeble that it is masked if the material also show magnetism of the other two types.

2. In paramagnetic materials, the spin and orbital magnetic dipole moments of the electrons in each atom do not cancel, but add vectorially to give the atom a net (and permanent) magnetic dipole moment. In the absence of an external magnetic field, these atomic dipole moments are randomly oriented, and the net magnetic dipole moment of the material is zero. However, if a sample of the material is placed in an external magnetic field, the magnetic dipole moments tend to line up with the field, which gives the sample a net magnetic dipole moment.

3. Ferromagnetic material is described as having strong, permanent magnetism- not a diamagnetic or paramagnetic material having a weak, temporary magnetism. Iron, cobalt, nickel, gadolinium, dysprosium, and alloys containing these elements exhibit ferromagnetism because of a quantum physical effect called

exchange coupling, in which the electron spins of one atom, interact with those of neighboring atoms. The result is alignment of the magnetic dipole moments of the atoms, in spite of the randomizing tendency of atomic collisions. This persistent alignment is what gives ferromagnetic materials their permanent magnetism.

If the temperature of a ferromagnetic material is raised above a certain critical value, called the *Curie temperature*, the exchange coupling ceases to be effective. Most such materials then become simply paramagnetic; that is, the dipoles still tend to align with an external field but much more weakly, and thermal agitation can now more easily disrupt the alignment.

In summary, a ferromagnetic material placed in an external magnetic field develops a strong magnetic dipole moment in the direction of that field. If the field is non-uniform, the ferromagnetic material is attracted <u>toward</u> a region of greater magnetic field <u>from</u> a region of lesser field. A time-varying magnetic field induces a voltage in any conductor linked by the field. The circuit parameter of *Inductance* relates the induced voltage to the current. Inductance is the circuit parameter used to describe an inductor, symbolized by the letter L, measured in henries, and is represented graphically as a coiled wire – a reminder that inductance is a consequence of a conductor linking a magnetic field.

Relating the voltage drop (which is WORK per unit charge) across the terminals of the inductor, we find:

$$V = L\, di/dt$$

Where V is measured in volts, L in henries, and t in seconds. It can immediately be seen that induced voltage becomes a function of a <u>frequency</u>, since the current is changing with time. Also, from this relationship, we can see that a di/dt increases for a given L, the voltage increases. Therefore, as frequency increases, the induced voltage will increase likewise. The current is charge per unit time, and di/dt becomes the acceleration of the charge. That, in turn, is proportional by L, to the voltage, or work (energy) per unit charge. L has *inertia,* as a mechanical mass does, and resists the change in current magnitude with time, so the resulting induced voltage compares to a mechanical *force*.
Thus, the inductor is really a device that stores energy in a magnetic field.

As the magnetic field is immersed in a medium such as iron, the ability to store energy is increased. This measure of the storage capability is referred to as *permeability*, labeled: μ. Here, permeability can be described as the ability to conduct the magnetic field, also noted as *flux*.

It is important at this point to note that permeability can be described more accurately with the concept of **complex permeability**: μ^*, in order to account for various parameters of all types of core material, including losses. As μ_0 represents the permeability of free space ($4\pi \times 10^{-7}$), μ_R would represent the relative permeability of a material with respect to free space. Loss processes in a core material are conveniently modeled as the imaginary component of the complex permeability:

$$\mu^* = \mu_0\mu_R^* = \mu_0(\mu' - j\mu'')$$

This relationship defines the loss tangent of a given core material, where μ_R^* consists of the vector sum of μ' and μ''. The loss component, the tangent of the angle enclosed by μ' and μ'', is defined to be $\tan \delta = \mu'/\mu''$.

As we loop conductors around an iron based core and provide a source of alternating current as shown below, there results a magnetizing force which is proportional to the number of turns N, and the current I.

$$H = kNI \qquad \text{(from Ampere's law, } k=0.4\pi/l)$$

This magnetizing force creates a flux _ in the core, here noted in flux per cross sectional area, or as flux density, B.

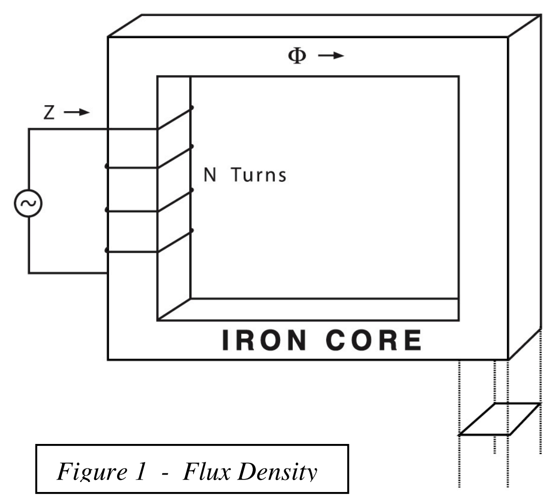

Figure 1 - Flux Density

When B is plotted against H, a curve is obtained which is called the 'magnetization' curve or 'saturation' curve and is shown below:

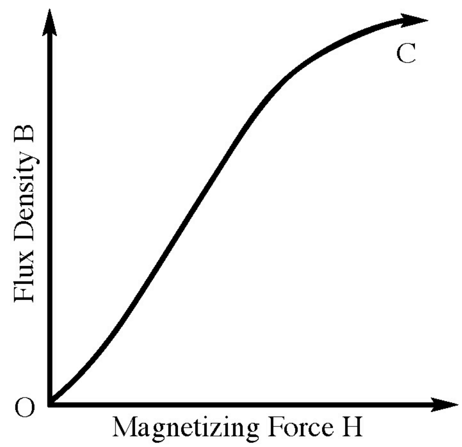

Figure 2 - Variation of B with H in a previously demagnetized specimen.

This is a B-H curve for a sample of material that had been previously, totally demagnetized and then subjected to a gradually increasing magnetizing force, H = NI, while the flux density B was measured. *The slope of this curve at any given point gives the* *<u>permeability</u>* *at that point. Permeability,* which is equal to $\Delta B/\Delta H$, is symbolized by the Greek letter μ, as noted above. μ is complex and is not constant or linear!

If a sinusoidal field is applied to a core of complex permeability,

$$H = H_{applied} \cos \omega t,$$

And assuming $B = \mu^* H$, then it follows that

$$B = \mu_0 H_{applied}(\mu' \cos\omega t + \mu'' \sin \omega t).$$

This relationship defines an ellipse, with the loss components μ' and μ'' depicting the 'fatness' of the loop.

The B-H curve clearly shows the meaning of saturation. It can be seen that beyond a certain value of H, (point C above) there is little increase in B; the iron is approaching saturation. Here the μ must be small or zero because there is little or no increase in B for an increase in H.

This means that the inductance is very small when the iron is taken into saturation.

If the field applied to a core is increased to saturation, and then decreased, the flux density B decreases, but not as rapidly as it increased along the initial magnetization curve. Thus, when H reaches zero, there is a residual flux density, or 'remanence', Br, *and the core is still magnetized.*

In order to reduce B to zero, a negative field –Hc must be applied. This is called the 'coercive' force. As H is further increased in the negative direction, the specimen becomes magnetized with the opposite polarity. The magnetization, at first, being easy and then hard as saturation is approached. Bringing the field to zero again leaves a residual magnetization or flux density –Br, and to reduce B to zero, a coercive force +Hc must be applied. With further increase in field, the specimen again becomes saturated with the original polarity.

The phenomenon, which causes B to lag behind H so the magnetization curve for increasing and decreasing fields is not the same, is called HYSTERESIS.

This curve shows that after the initial magnetization, the flux density always lags behind the magnetizing force H. As will be seen, herein lies the heart of the core loss situation. It also shows that the magnetized state of the material depends not only on the magnetizing *force* being currently applied, but also on the previous magnetic state.

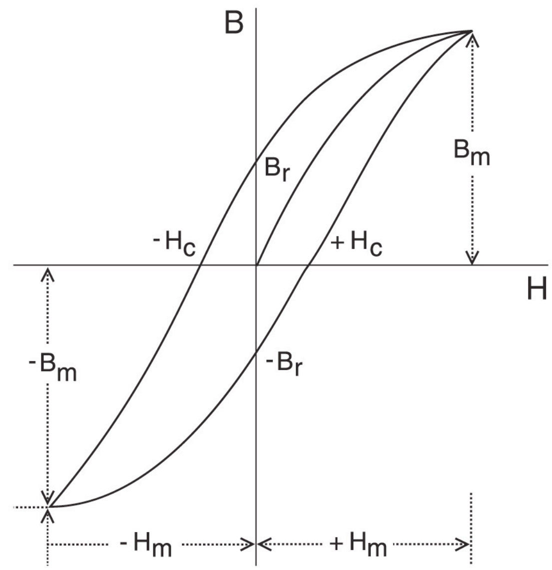

Figure 3 - Hysteresis

This hysteresis loop represents energy lost in the core, a kind of 'magnetic friction', which is additional to eddy current losses. The area of the hysteresis loop is a measure of the loss. The loss occurs since the magnetic field reverses direction every one half cycle of the applied voltage, and energy is expended, in doing so, in the core. Energy is work, which is fundamentally: a force moving through a distance, and, as voltage is the work per unit charge required to rise to a given higher potential, the *coercive* force involved in the B-H loop brings about an expenditure of *work* to complete the cycle.

This loss component is known as the HYSTERESIS loss Ph, and through empirical curve fitting and research, has been found to be given by the relation:

$$Ph = 150.7 \, Ve \, f \, Bm^{1.6} \quad \text{watts}$$

Where Ve is the volume of the core in cubic meters, f is the frequency, and Bm is the maximum flux density in teslas.

Further, as the magnetic field reverses direction and cuts across the core structure, it induces a voltage in the core known as 'eddy' voltages. *This action in turn causes <u>eddy currents</u> to circulate in the core*. Also, the lines of flux that link the copper conductor windings of the transformer pass through the core itself and contribute to inducing the electrical currents in it. These eddy currents heat up the core, thus wasting power.

According to Maxwell's equations, a time variation of flux density is necessarily accompanied by a curl of electric field:

$$\nabla \times E = -\frac{\delta B}{\delta t}$$

The integral form of the same equation states that a voltage drop must exist around any path that surrounds a time variation in flux.
The integral form becomes:

$$\int E dl = -\frac{d\phi}{dt}$$

The left-hand side is the voltage induced per turn, which is the integral of the electric field around the periphery of the core.
This integral form is also analogous to Ampere's circuital current law, which has the form:

$$\oint H dl = \iint I ds = I(enclosed)$$

If the path lies inside a magnetic core in which the flux is changing and cutting through, the voltage will induce a current if the core happens to be a conductor. This current is the eddy current spoken of.

Eddy currents tend to flow in a direction to oppose the flux change. That is, the H field of the eddy current is opposite to the applied field, thereby *shielding* the interior of the core from the applied field.

The loss due to eddy currents has been determined to be according to the following equation:

$$Pe = 1.65\ Ve\ B^2\ f^2\ t^2/r$$

Where Ve, B, and f are given above for Hysteresis loss, and t is the thickness of the core laminations in meters, and r is the resistivity of the core material in ohm-meters.

It is apparent that both hysteresis and eddy current losses increase with increasing frequency of the applied voltage. The eddy losses by the <u>square</u> of the frequency.

A magnetic core, whether it be a transformer or a motor or generator, is designed to operate at its fundamental frequency. And even at the fundamental frequency, depending upon the type and quality of core material used, hysteresis losses will occur. This is because there will always be a certain amount of magnetic retentivity associated with the B-H loop.

However, when high frequency electrical noise is added in the system, there will be effectively minor hysteresis loops for each frequency, and significant energy is expended in the core to support the flux transversals. The core can more easily be drawn into saturation because of the effective displacement in the core sustaining the eddy currents. Not only does this reduce the operating efficiency of the core, but energy is dissipated in heat. The permeability is reduced and circuitry surrounding the core, such as active switching devices, suffer because of the increased current load.

THE REASON FOR ABSORBING HYSTERECTIC AND EDDY CURRENT DISTURBANCES

It is most desirable for electrical equipment to operate from clean, sinusoidal voltage and current waveforms in order to achieve maximum efficiency. Poor power quality does involve pollution on the line resulting from high frequency induced electrical noise, switching transients, and nonlinear and unbalanced load reflections. Power surges, both voltage and current, are occurring continually in today's power systems. Whether they occur naturally, such as from lightning and static electricity, or man made, such as inductive surges from motors, transformers, solenoids, etc., power surges are a fact of life. These power surges have a very high voltage and current level as compared to electrical noise alone.

Electric systems endure abuse largely from spikes and transients (resulting in high frequency noise in the line) generated internally that perpetuate their own distortions indefinitely. This then reduces operating efficiency and creates excess heat that displaces normal power distribution and output. That in turn causes electrical systems and equipment to ultimately deteriorate and malfunction.

Further, in a digital logic control system, where binary bit patterns are used to implement control signals, random impulsive noise can knock out bits or put in bits where they should not exist. Thus, the control signal is altered and the desired action is lost. For this reason, it is important to inhibit the impulsive noise by clamping, filtering, and absorbing before reaching the circuitry that will try to correlate the oncoming binary signal.

And ultimately, this is the long term *POWER QUALITY* problem.

HYSTERESIS LOOP MONITORING AND ANALYSIS

A key component imbedded within all commercial and industrial power conversion systems is some type of magnetic core material. This iron-based material is incorporated as the essential part of every transformer, motor, generator, or AC conversion device.

The degree of power quality within a facility can largely be related to the conversion efficiency of the magnetic core components. A given core is characterized by the shape of its 'magnetization' or 'saturation' curve, wherein (as we have shown above in this report) flux density, B, is plotted with reference to magnetizing force, H.

Key factors such as Remanence, Coercivity, Permeability, Core Loss vs. Frequency, and Saturation magnitude, are important to be understood and quantitatively evaluated for a proposed core sample.

Since the hysteresis loop is displayed as an X-Y graph, where the magnetic field intensity (H) is represented on the X-axis and the magnetic flux density (B) is represented on the Y-axis, it is feasible to empirically obtain data concerning a given sample of prospective magnetic core material. This is to be done also to cross check the manufacturer's core data.

The core material under evaluation would be given two separate wire conductor test windings: a 'primary' and a 'secondary', each having a predetermined number of turns.

With that, consider the following relationships:

1. $H = 0.4\pi NpI/mpl$

   Where H = magnetic field intensity, Oersteds
   I = input current, Amperes
   Np= Number of primary turns
   Mpl= Magnetic path length, cm.

2. B = (Vo x 10^4)/(KFANs)

   Where B = Magnetic flux density, Tesla
   Vo = Output voltage (across secondary winding)
   K = Form factor (1.11 for a sine wave)
   F = Input frequency, Hz
   A = Cross sectional area of core, cm^2
   Ns = Number of secondary turns

From the above, it can be readily seen that for a given magnetic core to be placed under test, we can set up a predetermined number of primary turns, measure or obtain mpl, and set the input current, I.

Next, K, F, A, and Ns are predetermined and set. Now, as the input current (and thus H) is caused to vary over each cycle, the corresponding B can be determined by measuring and tracking Vo.

Varying Iin versus F for a given core will give a rather complete picture of the core losses, saturation, and linearity value of the permeability.

CAD tools, such as Labview or Simulink and other generator and display hardware can be incorporated as a test and evaluation system.

It is then possible for a development engineer to obtain a comprehensive analysis relating to virtually any proposed magnetic core material. This is to be done, in order that the best choice of core material and configuration can be established for a given power conversion application.

This analysis will greatly aid in the overall power quality development process.