ECE 3251 – Electromagnetic Energy Conversion
Lab #4: Magnetic Non-Linearities

Laboratory Goals

The purpose of this experiment is to familiarize you with the fundamental electromagnetic relationships and the magnetic properties of materials which underlie electromechanical energy conversion. You will observe on the oscilloscope that a sinusoidal voltage applied to a winding wrapped around a ferromagnetic core produces a sinusoidal flux but a non-sinusoidal excitation current. You will also observe the hysteresis loop of the core and the in-rush current produced when the voltage is first applied.

Background

The current drawn by the primary when the secondary is open-circuited is called the excitation current. If we excite the winding of our device with a sinusoidal voltage source, Faraday's law tells us that we will get a sinusoidal flux in the core which is 90º out of phase with the voltage (is that what you observed?). The current in the coil however may be non-sinusoidal due to the nonlinearity of the magnetization curve. A plot of flux vs current represents the magnetization (B vs H) curve of the device and is a very important characteristic of any machine or transformer. We may divide the magnetization curve into the linear region (where the permeability is large), and the saturation region (where μ is small), divided by a very non-linear region called the knee of the curve. (**Figure 1**)

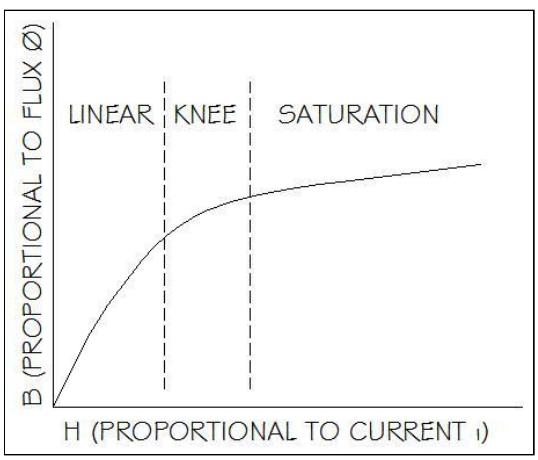

Figure 1 - Magnetization Curve

Observe that when the flux exceeds the knee of the curve and enters the saturation region, a small further increase in flux will require a large increase in current. The production of a non-sinusoidal exciting current by a sinusoidal flux in a non-linear core is illustrated in **Figure 2**.

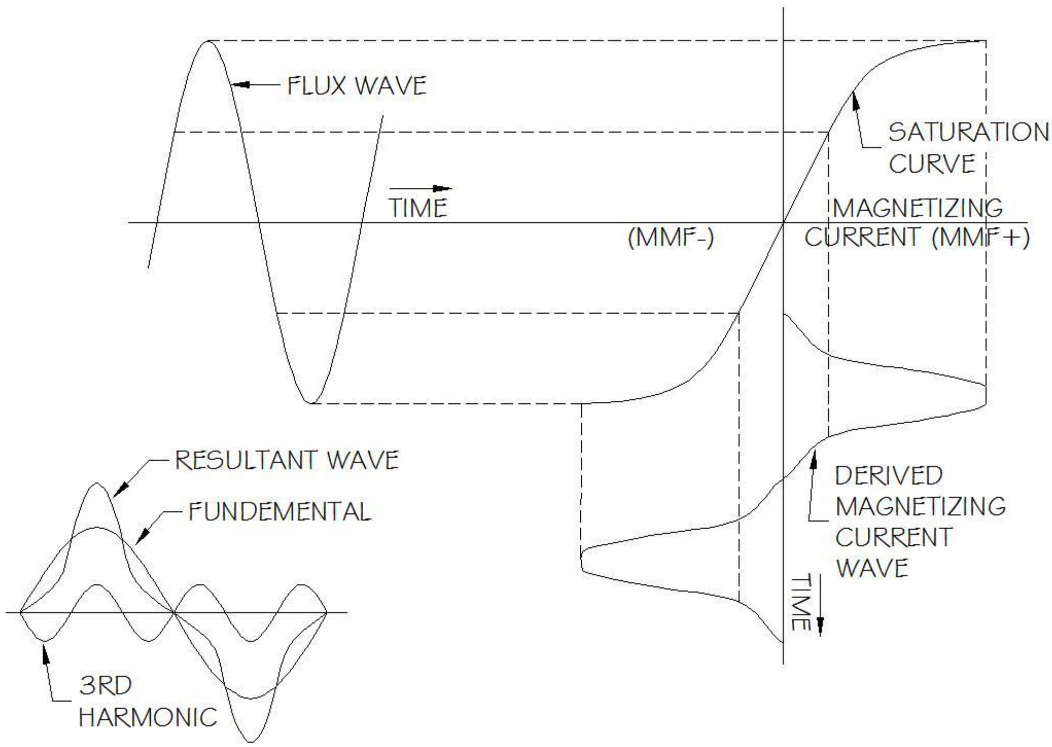

Figure 2 - Derivation of Magnetizing Current Wave from the Saturation Curve

The current waveform is periodic, however, and therefore may be analyzed by means of the Fourier series. The Fourier series will be a sum of:

1) A sinusoidal component at the same frequency as the applied voltage (called the fundamental) and
2) An infinite series of sinusoids at odd multiples of the fundamental frequency (called harmonics).

Note that total harmonic distortion is given by the following formula:

$$THD = \frac{\sum P_2 + P_3 + P_4 + \cdots}{P_1}$$

Where P_n represents the RMS power of harmonic 'n'.
(See http://en.wikipedia.org/wiki/Total_harmonic_distortion for more information)

As the sinusoidal flux in the core rises and falls, not only is the resulting current waveform non-sinusoidal, but it also lacks quarter-wave symmetry due to the fact that it has a different value for increasing flux than for decreasing flux. This phenomenon is called hysteresis, and is illustrated in **Figure 3**.

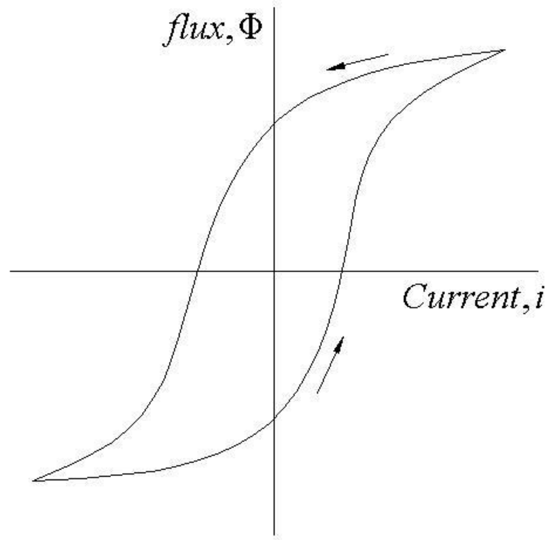

Figure 3 - Hysteresis Curve

The flux that remains when the exciting current (and thus voltage) is reduced to zero is called the residual flux. The area of the hysteresis loop is proportional to the energy consumed in reversing the magnetic domains of the magnetic material every half cycle, which is known as hysteresis loss.

Flux φ varies proportionately with the integral of the voltage over time, which results in essentially a 90° phase shift.

$$\varphi = \frac{1}{N}\int v(t)dt$$

The LabVIEW program used to generate the hysteresis curve takes advantage of this property. A scaled, phase-shifted version of the voltage is graphed on the Y-axis against the current on the X-axis.

Lab Procedures:

In this experiment we will use a single winding of a transformer connected to observe Ampere's and Faraday's law in a ferromagnetic core. The experimental setup is illustrated in the following schematic (**Figure 4**). The secondary winding X1 – X3 provides a sample of the induced voltage, and is applied to the second voltage input channel on the Data Acquisition Panel.

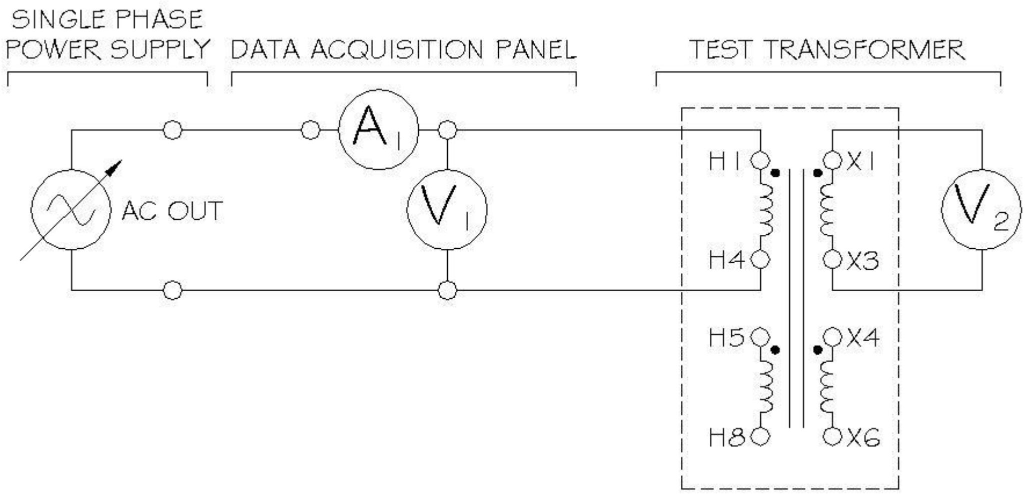

Figure 4 - Experimental Setup Schematic

1. Connect the transformer to the Single-Phase Power Supply panel and Data Acquisition panel as shown in **Figure 4**.
2. Open the PowerLab LabVIEW program and click on the Advanced Power Measure Display button.
3. Turn on the power and turn up the variac to 10V, and take the following measurements and calculations:
   a. RMS voltage, RMS current, and Power
   b. Use the 'VIP' method to calculate the series impedance.
   c. Record the peak value of the current from the graph. This is easiest to do by right-clicking on the graph and turning on the Autoscale Y. Once the voltage is set, turn the Autoscale off so that the curve isn't so jittery.
   d. From the Harmonic Spectrum window, record the RMS fundamental and RMS third harmonic components of the power waveform. Click and drag the yellow cursor crosshairs to the peak of each harmonic to measure it.
   e. Calculate the total harmonic distortion from the first and third harmonics. Note that the RMS values given in LabVIEW are for current, so be sure to use the appropriate relation to convert to power (power being proportional to the square of the current).
4. Repeat all parts of Step 3 at 10V increments from 10V to 120V. In addition, at 80V and 120V, take a screenshot of the current graph and of the hysteresis curve.
5. Connect X4 & X6 to the resistive load on the AC LOAD PANEL. Turn the variac up to 60V and then 120V and look at the hysteresis curve. Make note of how is the hysteresis curve different from the case where there is no load.

Post-Lab Calculations and Questions:

1. What do you notice about how the shape of the hysteresis curve changes based on the phase difference of the voltage and current?
2. Using the peak value of the current obtained in Step 3c above, determine the "crest factor" for each current. The crest factor is the ratio of the peak value of the waveform to its RMS value. What is the crest factor for a plain sinusoidal signal?
3. Why is the flux sinusoidal but the current non-sinusoidal when we apply a sinusoidal voltage?
4. Why is the current sinusoidal at low voltages but becomes non-sinusoidal at higher

voltages?

5. Graph excitation current (the RMS current you measured) as a function of supply voltage. What is the value of the voltage at which saturation occurs?
6. Can you determine the value of the flux? If so, what expression would you use to find the flux? If not, what additional information would you need?
7. Use fundamental relationships and equations developed in class to show that φ vs. i is equivalent to B vs. H on the hysteresis loop.
8. The hysteresis curve changes when there is a load on the transformer. What can you say about the effect a load on the transformer has on the magnetic flux density in the core?

Grading

- Formal report: Organization, neatness, clear writing, proper formatting of graphs, figures, tables, etc. (15 points)
- Lab Participation: Contributions from each lab partner are fairly distributed and documented (10 points)
- Introduction: What is the purpose of this lab? (5 points)
- Procedures: Brief account of the steps to obtain results (10 points)
- Results: Measurements and calculations for each lab step (30 points)
- Conclusions: Analysis, explanation of data, and post lab questions (30 points)