5. Experiment J: Transformers

5.1. Introduction.

During this experiment you will attempt to design and build a transformer which provides an isolated supply of exactly 6A into a 0.11Ω resistor, given a 12V 0.5A 50Hz supply. The transformer has two windings each rated at 9V 0.67A which serve as a primary. No extra components may be connected in series or in parallel with the 0.11Ω load. You will have to wind a suitable secondary winding.

The purpose of this experiment is to help the student become familiar with

(i) The construction of low frequency transformers
(ii) The relationship between magnetic flux, induced EMF and magnetising current
(iii) The idea of a magnetic circuit
(iv) The limitations of iron as a magnetic material
(v) One of the simplest equivalent circuits for the transformer
(vi) Calculations based on a.c. voltages and currents
(vii) The sources of loss in a transformer and the effect of frequency on the relative magnitude of these losses.

Although your experiment deals with a transformer of a few VA, the equivalent circuit applies to transformers of any size including those found in power stations rated at 500MVA or so, although the relative magnitude of the circuit parameters will differ. All equivalent circuits are approximations but the one you will use is fairly simple compared to those presented in many textbooks.

5.2. Preliminary Work

Section 6: “Transformer theory” provides additional information needed for this experiment, together with a layout drawing for the test jig provided. Ensure you are familiar with the basic principles of electromagnetism and transformers prior to completing this experiment.

You should read through this experimental guide and deal with the points below.

(a) Why are transformers rated in VA and not W?

(b) Study the constructional details of the transformer illustrated by figure 1.

   o Calculate the mean length of the flux path and cross sectional area of the flux path through the coils.

   o What is meant by the term “Stacking Factor” (for the experiment use 0.96 for your calculations)?

   o Why are the E & I laminations inserted either side rather than having all the E’s on one side and all the I’s on the other side? The answer is NOT to stop the transformer falling apart!
Note: some transformers do have all E’s on one side and all I’s on the other – comment on possible advantages and disadvantages of this arrangement, and where it may find application if there is sufficient time at the end of the experiment.

Figure 5-1: Transformer construction detail.
(c) Using the B-H curve provided above in Figure 5-2, find the saturation flux density for the transformer, and the slope of the B-H curve. From the slope calculate a typical value for the relative permeability of the steel used.

(d) Make sure you have read, and understand Section 6: Transformer Theory, if you have not – do so before continuing any further at this point.

(e) Assuming a peak flux density of 1.4T estimate the number of turns for one of the 9V windings of the transformer and the magnetising current taken if this winding is supplied at 9V. Why is this value of current unacceptable? (In practice the 9V windings are secondaries and the 230V primary has been removed for safety reasons.)
5.3. Experimental Work

To carry out the experiment you will need the following equipment:

- Experiment J PCB assembly
- Orange shorting link (this should be fitted to the board in the park position)
- 5A Variac (0-275V ac output)
- 230-18V (2 x 9V in series) 0.5A fused isolating transformer (grey box) – Note, this is used to provide a 0-20V AC supply, achieved by increasing the input voltage above 230v using the Variac.
- 2 x 50Ω BNC leads
- Dual Trace Oscilloscope (Tektronix TDS210 or equivalent)
- Clean, low distortion 50Hz Sinusoidal AC supply; available from Red socket outlet.
- 20V pk-pk 600Ω Signal generator with isolating transformer. (only required at end of experiment)
- AVO 8 with leads (optional)
- Qty of 1.18mm² Enamelled Copper wire & glass paper to clean ends
- Connecting leads and hand tools as required (tools to be provided by student)

![Figure 5-3: Circuit used for Low Frequency Investigation.](image)

**Analysis**

(a) Wind 10 turns on your transformer using the space provided, clean the enamel insulation from each end of the wire leaving approx 15mm of exposed copper. Connect the ends to the terminals provided on the board and firmly tighten. Ensure that the link is parked, or not fitted at this stage. Connect the outputs of the grey isolating transformer in series so to provide a 0-20V AC supply and connect to the experiment board, using 4mm leads to terminals marked LF Pri (H) & (C).
Connect the oscilloscope Channel 1 input to the BNC socket “LF Pri Current”, and Channel 2 input to the BNC socket “LF Pri Volts” using the 50Ω BNC Leads provided.

Monitor and sketch the magnetising current waveform (CH1) and primary voltage waveform (CH2). (Hint: produce a table of values of input voltage, output voltage and magnetising current, use 2V steps, 0-20V for the input voltage, remember to include scope settings with sketches.) Estimate the value of magnetising current for a single 9V winding, when supplied at 9V. How does this relate to your preliminary calculations?

(b) Measure the open circuit EMF of the secondary winding with 15V as the primary voltage and calculate the number of primary turns, and the RMS and peak values of flux density in the magnetic core.

(c) Turn off the supply and change connections to the test set up as follows: Connect the oscilloscope Channel 1 input to the BNC socket “LF Pri Current”, (as before) and connect the oscilloscope Channel 2 input to the BNC socket “LF Sec Int”.

The network, which consists of a 100kΩ resistor and a 1µF capacitor, provides a signal proportional to the integral of the EMF. Check the expected phase shift by calculation, and display the flux and magnetising current waveforms simultaneously. Explain the waveforms.

(d) Using the flux signal and the magnetising current as X & Y respectively on the oscilloscope, display the B-H curves for the core material and scale in terms of Tesla and Ampere Turns per Metre. Set the primary voltage to 18V for your measurements; also observe how the shape of the loop changes as the primary voltage is reduced.

(e) Reconnect the oscilloscope to display the primary voltage (18V) and magnetising current waveforms simultaneously. The current waveform should be predominantly a mixture of 50Hz and it’s third harmonic. It is necessary to find the component of the 50 Hz current in phase with the voltage and also the component lagging the voltage by 90°. The method described below together with Figure 5-4 illustrates one approach. Having obtained these two components of the 50 Hz current, the values of core loss, \( R_m \) and \( X_m \) in the equivalent circuit can be calculated. Does this method work in the presence of 5\(^{th}\), 7\(^{th}\) etc. harmonics?

**Method.**

Assume that the magnetising current waveform can be represented by 3 components: 2 sinusoidal signals one in phase with the voltage waveform, labelled \( I_y \) and the other lagging the voltage waveform by 90° labelled \( I_x \), and a third signal at 3 x the frequency – i.e. a 3\(^{rd}\) harmonic component labelled \( I_{harmonic} \).

We need to know the amplitude of the component in phase with the voltage waveform and the amplitude of the waveform lagging the voltage waveform by 90°.
By selecting sample point’s t1 and t2, at 60° and 120° it can be seen that both the sums of the instantaneous amplitudes of waveforms Ix and I_{harmonic} cancel out. Note that the phase of the 3rd harmonic component is not relevant since the 60° difference relative to the fundamental is equivalent to a 180° difference relative to the 3rd harmonic component so the samples will always cancel out regardless of the phase relationship between the harmonic and the fundamental component. As far as Ix is concerned, we simply need two symmetrical points 60° apart (because of the 3rd harmonic cancellation required – see above) either side of the zero crossing point at 90°, hence the use of 60° and 120° for t1 and t2.

Summing the products of instantaneous voltage and instantaneous current at point’s t1 and t2 as illustrated above gives:

\[ 2 \times (0.866 \times V_{pk} \times 0.866 \times I_{y \, pk}) = 3 \times V_{rms} \times I_{y \, rms} \]

(Amplitude at Sin 60° = Sin 120° = 0.866 x peak amplitude, Real power = \(V_{rms} \times I_{y \, rms}\))

So, using your results, Real power = \(\frac{1}{2} \times ((V_{(t1)} \times I_{(t1)}) + (V_{(t2)} \times I_{(t2)})\)

Considering the case for the component lagging V by 90° we now use points t3 and t4 at 150° and 210° respectively to eliminate I_y. The approach used above cannot be directly applied to this case since the current lags the voltage by 90°.

Note: Sin (150°-90°) = Sin 60° and Sin (210°-90°) = Sin 120° = 0.866 applicable to the current component to accommodate the phase relationship between V & I.

Also, note for the above example, Sin 210° = -0.5, however the voltage at point t4 is also negative so the formulae provided has been simplified taking this into account by considering in terms of magnitude only.
Hence, taking the sum of the magnitudes of products of instantaneous voltage and instantaneous current at t3 & t4 leads to:

$$2 \times (0.5 \times V_{pk} \times 0.866 \times I_{x\,pk}) = 1.732 \times V_{rms} \times I_{x\,rms}$$

i.e. $1.732$ x reactive power consumption of circuit (VAr)

To Calculate: $\text{VAr} = \frac{1}{\sqrt{3}} \times ((|V(t3)\times I(t3)|) + (|V(t4)\times I(t4)|))$

(f) With the supply voltage from the Variac set to zero, and the oscilloscope set up to monitor the current – use the readout facility to display the RMS voltage - which is numerically equivalent to the rms current due to the choice of a 1Ω sampling resistor in the circuit, short circuit the secondary winding by tightly clamping both ends of the winding under the same terminal. Note - a good electrical connection at this point is essential as the secondary current will be several amps. Next, raise the supply voltage using the Variac gradually and carefully just until the current in the primary as monitored by the scope reaches 0.5A. **Do not exceed this current as the transformer primary winding will overheat and burn out --- you will then have to rewind this by hand, and there are a lot of turns!**

Display the primary voltage waveform on channel 2 of the oscilloscope. Why is the current virtually sinusoidal? Measure the phase shift between voltage and current and then calculate the series values $R$ and $X$ in the equivalent circuit. Why can the magnetising branch be neglected in this test?

**Design**

You are now in a position to design your secondary winding to give exactly 6A in the 0.11Ω load resistor, with the primary voltage adjusted to exactly 12V. Using the information provided in Section 6 in conjunction with the material studied so far, calculate the number of secondary turns to give the required voltage output when connected to the load. Clearly choosing the number of secondary turns to give the required output voltage into an open circuit will not provide a solution, extra turns are needed to compensate for the voltage regulation (i.e. allow for the drop in $R$ & $X$ – see equivalent circuit in Section 6). Fortunately with a resistive load, the analysis is easy, because the majority of the voltage drop in respect to regulation can be attributed to the winding resistance $R$, where $R$ is the primary resistance together with the secondary resistance as viewed from the primary. (Note, temperature effects are neglected for the purposes of this work).

As the number of secondary turns are changed, the primary current will vary, and the secondary resistance will change (different wire length), and so the value seen from the primary side will change by reason of the change in ratio and secondary resistance. In other words the value of $R$ in the equivalent circuit will vary a little and you will either have to write some equations or use your judgment in choosing the correct number of secondary turns.
Wind the new secondary winding and test with the 0.11 ohm load. **Take Care when testing, the surface temperature of the load resistor could be very high – several hundred °C, even if your design is correct.** You must not connect any components in series or in parallel with the load other than the voltmeter used to measure the secondary voltage using the connections on the test bed provided. For example, connecting an AVO meter set to read current in series with the load would substantially alter the current – so do not try to. To connect the load to the secondary, remember to fit the link into the correct position to connect the load. (“Link to connect Load”)

When you have adjusted your winding and determined that it provides the specified output:

(a) Calculate the efficiency of your transformer by observing the input current and voltage waveforms using techniques described previously, measure the voltage across the load resistance and calculate the output power.

(b) Calculate the voltage regulation from voltage measurements with the transformer open circuit and with the transformer connected to the load. Remember to keep the input voltage at 12V, we do not want the voltage regulation of the whole supply system (isolating transformer, AC supply filter, Variac etc. back to the power station generator!)

### Further Work

![Figure 5-5: used for HF investigation as fitted to Transformer Experiment board J.](image)

a) Investigate the magnetic characteristics at different frequencies up to a few tens of kHz, using the waveform generator. The generator must be isolated either by using a separate mains isolation transformer, or by connecting a suitable AF isolating transformer in line with the output of the generator.

If directly connected, make sure the waveform generator has a 600Ω output impedance and if this is not the case, add a 47Ω resistor in series to protect the generator.
You should study the phase shift between the primary voltage and magnetising current. Why is this phase shift zero at about 20kHz?

If you follow the procedure to find \( R_m \) (representing the losses in the iron) it may come as a surprise that \( R_m \) has a high ohmic value. However, from the terminal voltage and frequency you will understand that the flux density in the iron is very low indeed. Calculate the terminal voltage at 20kHz necessary to give the same flux density as you were using at 50Hz. The new value for eddy current and hysteresis loss in the iron can then be calculated with surprising results. This is the principal of induction heating used widely in manufacturing industry.

b) Repeat the higher frequency investigation with a ferrite cored pulse transformer. The rating is 200 Volt-microsecond. What does this rating mean and are eddy currents important in this device? Note that the integrating network provided on the experiment board for the HF circuit is different to the one used for the iron cored transformer – see Figure 5-5 for details.

**To Finish**

Disconnect all equipment, remove your windings and return any leads or other equipment taken from racks and cupboards as appropriate. Leave the laboratory tidy, remember to put any rubbish in the bins provided. Thank you.

< The End >

Based on an original experiment devised by P.Marshall – October 1990

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6. Transformer theory – Required for Experiment J.

For those unfamiliar with the basic principles of transformers – please see:

http://en.wikipedia.org/wiki/Transformer

Suppose a magnetic flux $\Phi_a$ circulates in the iron, linking the two coils (Primary winding to Secondary winding) as illustrated below.

Then,

$$V_1 = N_1 \frac{d(\Phi_a + \Phi_b)}{dt} \quad \text{and} \quad V_2 = N_2 \frac{d(\Phi_a + \Phi_c)}{dt}$$

Note that the fluxes $\Phi_b$ and $\Phi_c$ are leakage, the induced EMF’s in the coils resulting from these fluxes are represented by the voltages across the leakage reactance $X$ in the equivalent circuit – see next page.

Let $\Phi_a = \sqrt{2} \Phi_{a \text{ rms}} \sin \omega t$ then,

$$V_{1 \text{ rms}} = N_1 \omega \Phi_{a \text{ rms}} \quad \text{and} \quad V_{2 \text{ rms}} = N_2 \omega \Phi_{a \text{ rms}} \text{ neglecting leakage}$$

The magnetic flux density is given by:
\[ B_{\text{rms}} = \frac{\Phi_{a,\text{rms}}}{A} \quad \text{and we know that;} \]

\[ B = \mu_0 \mu_r H \quad \text{and so,} \quad H_{\text{rms}} = \frac{B_{\text{rms}}}{\mu_0 \mu_r} \]

The magnetizing current necessary to set up the flux \( \Phi_a \) is therefore given by:

\[ I_{\text{mag, rms}} = \frac{L B_{\text{rms}}}{\mu_0 \mu_r N_1} \]

This current will be in phase with the flux and displaced by 90° from the EMF. It may also contain harmonics because of the non-linear relationship between flux and current.

The magnetizing current will also contain a component in phase with the EMF which supplies the hysteresis and eddy current losses in the magnetic core.

These effects are represented by \( X_m \) and \( R_m \) in the equivalent circuit.

Parameters can be transferred from one side of the transformer model to the other. For example \( R \) appearing on the primary side represents both the primary and secondary winding resistance.
PCB Layout for Transformer Experiment J